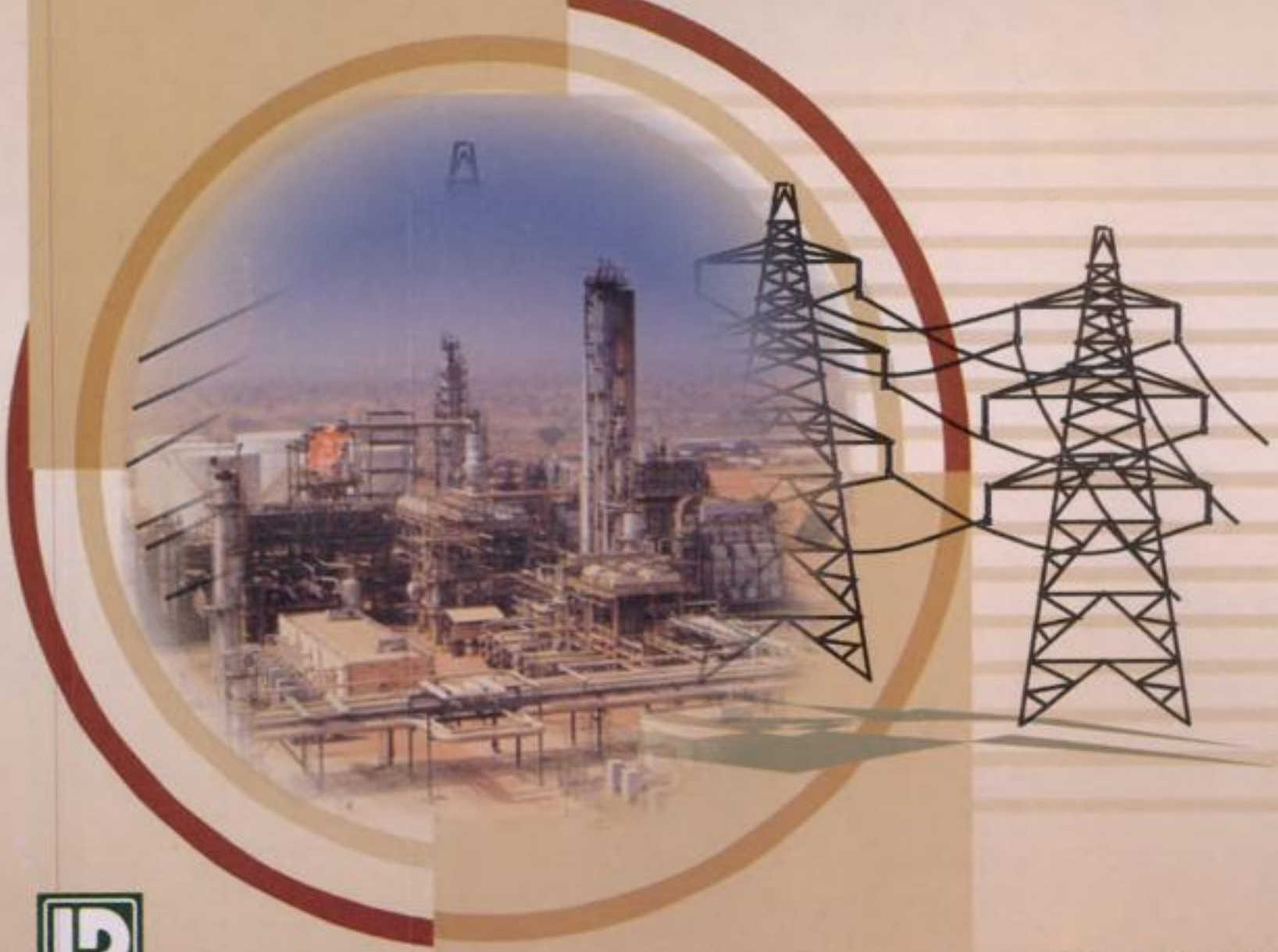
A TEXTBOOK OF

POWER SYSTEM ENGINEERING



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4. Gas Turbine Power Plants
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8. Combined Operation of Different Power Plants
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1

Introductory

1.1. Energy 1.2. Power 1.3. Sources of energy—Fuels—solid fuels—liquid fuels—gaseous fuels—calorific or heating values of fuels—Energy stored in water—Nuclear energy—Wind power—Solar energy—Tidal power—Geothermal energy—Thermo-electric power. 1.4. Power systems' structure. Highlights—Theoretical Questions.

1.1. ENERGY

- **Energy** probably was the *original stuff or creation.* It appears in many forms, but has one thing in common— *energy is possessed of the ability to produce a dynamic, vital effect.* It shows itself by *excited animated state* assumed by material which receives energy.
- Energy exists in various forms, *e.g., mechanical, thermal, electrical* etc. One form of energy can be converted into other by the use of suitable arrangements.
- **Electric energy** is an essential gradient for the industrial and all-around development of any country. It is preferred one to the following *advantages* :

  (*i*) Can be generated centrally in bulk.

  (*ii*) Can be easily and economically transported from one place to another over long distances.

  (*iii*) Losses in transport are minimum.

  (*iv*) Can be easily sub-divided.

  (*v*) Can be adapted easily and efficiently to domestic and mechanical work.
- **Electric energy** is obtained, conventionally, by *conversion from fossil fuels (coal, oil, natural gas), the nuclear and hydro sources.* Heat energy released by burning fossil fuels or by fusion of nuclear material is converted to electricity by first converting heat energy to the mechanical form through a thermocycle and then converting mechanical energy through generators to the electrical form. Thermo-cycle is basically a low efficiency process—highest efficiencies for modern large size plants range upto 40%, while smaller plants may have considerably lower efficiencies. The *earth has fixed non-replenishable resources of fossil fuels and nuclear materials. Hydro-energy*, though replenishable, is also *limited in terms of power.*
- In view of the ever increasing per capita energy consumption and exponentially rising population, the earth's non-replenishable fuel resources are not likely to last for a long time. Thus a coordinated world-wide action plan is, therefore, necessary to ensure that energy supply to humanity at large is assured for a long time and at low economic cost. The following factors needs to considered and actions to be taken accordingly : (*i*) *Energy consumption curtailment* ; (*ii*) *To initiate concerted efforts to develop alternative sources of energy including unconventional sources like solar, tidal, geothermal energy etc.* ; (*iii*) Recycling of *nuclear wastes* ; (*iv*) *Development and application of antipollution technologies.*

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1.2. POWER

- Any physical unit of energy when divided by a unit of time automatically becomes a *unit of power*. However, it is in connection with the mechanical and electrical forms of energy that the term *"power"* is generally used. The rate of production or consumption of heat energy and, to a certain extent, of radiation energy is not ordinarily thought of as power. *Power is primarily associated with mechanical work and electrical energy*. Therefore, **power** can be defined as the *rate of flow of energy* and can state that a *power plant* is a *unit built for production and delivery of a flow of mechanical and electrical energy*.
- In common usage, a machine or assemblage of equipment that produces and delivers a flow of mechanical or electrical energy is a **power plant.** Hence, an internal combustion engine is a power plant, a water wheel is a power plant, etc. However, what we generally mean by the term is that assemblage of equipment, permanently located on some chosen site which receives raw energy in the form of a substance capable of being operated on in such a way as to produce electrical energy for delivery from the power plant.

1.3. SOURCES OF ENERGY

The various sources of energy are :

1. Fuels	Solids—Coal, coke anthracite etc. Liquids—Petroleum and its derivatives Gases—Natural gas, blast furnace gas etc.	Conventional
2. Energy stored in water		Non-conventional
3. Nuclear energy		
4. Wind power		
5. Solar energy		
6. Tidal power		
7. Geothermal energy		
8. Thermoelectric power.		

1.3.1. Fuels

Fuels may be chemical or nuclear. Here we shall consider chemical fuels only.

A chemical fuel is a substance which releases heat energy on combustion. The principal combustible elements of each fuel are *carbon* and *hydrogen*. Though *sulphur* is a combustible element too but its presence in the fuel is considered to be *undesirable.*

Classification of fuels :

Fuels can be *classified* according to whether :

1. They *occur in nature* called *primary fuels* or are *prepared* called *secondary fuels.*
2. They are *in solid, liquid* or *gaseous state.*

The detailed classification of fuels can be given in a summary form as below :

Type of fuel	*Natural (Primary)*	*Prepared (Secondary)*
Solid	Wood	Coke
	Peat	Charcoal
	Lignite coal	Briquettes.

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Liquid	Petroleum	Gasoline
		Kerosene
		Fuel oil
		Alcohol
		Benzol
		Shale oil.
Gaseous	Natural gas	Petroleum gas
		Producer gas
		Coal gas
		Coke-oven gas
		Blast furnace gas
		Carburetted gas
		Sewer gas.

1.3.1.1. Solid fuels

Coal. Its main constituents are carbon, hydrogen, oxygen, nitrogen, sulphur, moisture and ash. Coal passes through different *stages* during its formation from vegetation. These stages are enumerated and discussed below :

Plant debris-Peat-Lignite-Brown coal-Sub-bituminous coal-Bituminous coal-Semi-bituminous coal-Semi-anthracite coal-Anthracite coal-graphite.

Peat. It is the first stage in the formation of coal from wood. It contains huge amount of moisture and therefore it is dried for about 1 to 2 months before it is put to use. It is used as a domestic fuel in Europe and for power generation in Russia. In India it does not come in the categories of good fuels.

Lignites and brown coals. These are intermediate stages between peat and coal. They have a woody or often a clay like appearance associated with high moisture, high ash and low heat contents. Lignites are usually amorphous in character and impose transport difficulties as they break easily. They burn with a smoky flame. Some of this type are suitable for local use only.

Bituminous coal. It burns with long yellow and smoky flames and has high percentages of volatile matter. The average calorific value of bituminous coal is about 31350 kJ/kg. It may be of two types, namely *caking* or *non-caking*.

Semi-bituminous coal. It is softer than the anthracite. It burns with a very small amount of smoke. It contains 15 to 20 per cent volatile matter and has a tendency to break into small sizes during storage or transportation.

Semi-anthracite. It has less fixed carbon and less lustre as compared to true anthracite and gives out longer and more luminous flames when burnt.

Anthracite. It is very hard coal and has a shining black lustre. It ignites slowly unless the furnace temperature is high. It is non-caking and has high percentage of fixed carbon. It burns either with very short blue flames or without flames. The calorific value of this fuel is high to the tune of 35500 kJ/kg and as such is *very suitable for steam generation*.

Wood charcoal. It is obtained by destructive distillation of wood. During the process the volatile matter and water are expelled. The physical properties of the residue (charcoal) however, depends upon the rate of heating and temperature.

Coke. It consists of carbon, mineral matter with about 2% sulphur and small quantities of hydrogen, nitrogen and phosphorus. It is solid residue left after the destructive distillation of certain kinds of coals. It is smokeless and clear fuel and can be produced by several processes. It is mainly used in blast furnace to produce heat and at the same time to reduce the iron ore.

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Briquettes. These are prepared from fine coal or coke by compressing the material under high pressure.

Analysis of coal :

The following two types of analysis is done on the coal :

1. Proximate analysis.
2. Ultimate analysis.

1. **Proximate analysis.** In this analysis, *individual elements are not determined ; only the percentage of moisture, volatile matters, fixed carbon and ash are determined.*

Example. Moisture = 4.5%, volatile matter = 5.5%, fixed carbon = 20.5%.

This type of analysis is easily done and is for *commercial purposes* only.

2. **Ultimate analysis.** In the ultimate analysis, the percentage of various elements are determined.

Example. Carbon = 90%, hydrogen = 2%, oxygen = 4%, nitrogen = 1%, sulphur = 15% and ash = 1.5%.

This type of analysis is useful for *combustion calculations.*

Properties of coal :

Important properties of coal are given below :

1. Energy content or heating value.
2. Sulphur content.
3. Burning characteristics.
4. Grindability.
5. Weatherability.
6. Ash softening temperature.

A *good coal should have* :

(*i*) Low ash content and high calorific value.

(*ii*) Small percentage of sulphur (less than 1%).

(*iii*) Good burning characteristics (*i.e.* should burn freely without agitation) so that combustion will be complete.

(*iv*) High grindability index (in case of ball mill grinding).

(*v*) High weatherability.

Ranking of coal :

ASME and ASTM have accepted a specification based on the fixed carbon and heating value of the mineral matter free analysis.

- **Higher ranking** is done on the basis of fixed carbon percentage (*dry basis*).
- **Lower ranking** is done on the heating value on the *moist basis.*

Example. 62% C and a calorific value of 5000 kcal/kg is ranked as (62—500) rank.

Rank is an inherent property of the fuel depending upon its relative progression in the classification process.

Grading of coal :

Grading is done on the following basis :

(*i*) Size
(*ii*) Heating value
(*iii*) Ash content
(*iv*) Ash softening temperature
(*v*) Sulphur content.

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Example. A grade written as 5—10 cm, 5000-A8-F24-S1.6 indicate the coal as having :

—a size of 5–10 cm,

—heating value of 5000 kcal/kg,

—8 to 10% ash,

—ash softening temperature of 2400—2590°F, and

—a sulphur content of 1.4 to 1.6%.

A rank and grade of a coal gives a complete report of the material. Thus the following are the rank and grade of the coal described above :

(62—500), 5—10 cm, 500-A8-F24-S1.6.

1.3.1.2. Liquid fuels

The chief source of liquid fuels is petroleum which is obtained from wells under the earth's crust. These fuels have proved *more advantageous in comparison to sold fuels* in the following respects.

Advantages :

1. Require less space for storage.
2. Higher calorific value.
3. Easy control of consumption.
4. Staff economy.
5. Absence of danger from spontaneous combustion.
6. Easy handling and transportation.
7. Cleanliness.
8. No ash problem.
9. Non-deterioration of the oil in storage.

Petroleum. There are different opinions regarding the origin of petroleum. However, now it is accepted that petroleum has originated probably from organic matter like fish and plant life etc., by bacterial action or by their distillation under pressure and heat. It consists of a mixture of gases, liquids and solid hydrocarbons with small amounts of nitrogen and sulphur compounds. In India the main sources of petroleum are Assam and Gujarat.

Heavy fuel oil or crude oil is imported and then refined at different refineries. The refining of crude oil supplies the most important product called *petrol*. Petrol can also be made by polymerization of refinery gases.

Other liquid fuels are kerosene, fuels oils, colloidal fuels and alcohol.

The following table gives *composition* of some common liquid fuels used in terms of the elements in *weight percentage.*

Fuel	*Carbon*	*Hydrogen*	*Sulphur*	*Ash*
Petrol	85.5	14.4	0.1	—
Benzene	91.7	8.0	0.3	—
Kerosene	86.3	13.6	0.1	—
Diesel oil	86.3	12.8	0.9	—
Light fuel oil	86.2	12.4	1.4	—
Heavy fuel oil	88.3	9.5	1.2	1.0

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Important properties of liquid fuels :

(1) Specific gravity (2) Flash point
(3) Fire point (4) Volatility
(5) Pour point (6) Viscosity
(7) Carbon residue (8) Octane number
(9) Cetane number (10) Corrosive property
(11) Ash content (12) Gum content
(13) Heating value (14) Sulphur content.

The requisite properties vary from device to device which uses the fuel to generate power. For example, *higher the octane number, higher can be the compression ratio and the thermal efficiency will be higher.* Similarly, *the cetane number of a diesel oil should be as high as possible.*

In general the liquid fuels should have :

(*i*) Low ash content (*ii*) High heating value
(*iii*) Low gum content (*iv*) Less corrosive tendency
(*v*) Low sulphur content (*vi*) Low pour point.

Viscosity and other properties vary from purpose to purpose to which the fuel is employed.

1.3.1.3. Gaseous fuels

Natural gas. The main constituents of natural gas are methane (CH_4) and ethane (C_2H_6). It has calorific value nearly 21000 kJ/m^3. Natural gas is used alternately or simultaneously with oil for internal combustion engines.

Coal gas. This gas mainly consists of hydrogen, carbon monoxide and hydrocarbons. It is prepared by carbonisation of coal. It finds its use in boilers and sometimes used for commercial purposes.

Coke-oven gas. It is obtained during the production of coke by heating the bituminous coal. The volatile content of coal is driven off by heating and major portion of this gas is utilised in heating the ovens. This gas must be thoroughly filtered before using in gas engines.

Blast furnace gas. It is obtained from smelting operation in which air is forced through layers of coke and iron ore, the example being that of pig iron manufacture where this gas is produced as by product and contains about 20% carbon monoxide (CO). After filtering it may be blended with richer gas or used in gas engines directly. The heating value of this gas is very low.

Producer gas. It results from the partial oxidation of coal, coke or peat when they are burnt with an insufficient quantity of air. It is produced in specially designed retorts. It has low heating value and in general is suitable for large installations. It is also used in steel industry for firing open hearth furnaces.

Water or Illuminating gas. It is produced by blowing steam into white hot coke or coal. The decomposition of steam takes place liberating free hydrogen and oxygen in the steam combines with carbon to form carbon monoxide according to the reaction :

$$C + H_2O \longrightarrow CO + H_2$$

The gas composition varies as the hydrogen content if the coal is used.

Sewer gas. It is obtained from sewage disposal vats in which fermentation and decay occur. It consists of mainly marsh gas (CH_4) and is collected at large disposal plants. It works as a fuel for gas engines which is turn drive the plant pumps and agitators.

Gaseous fuels are becoming popular because of following *advantages* they possess :

Advantages :

1. Better control of combustion.

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2. Much less excess air is needed for complete combustion.
3. Economy in fuel and more efficiency of furnace operation.
4. Easy maintenance of oxidizing or reducing atmosphere.
5. Cleanliness.
6. No problem of storage if the supply is available from public supply line.
7. The distribution of gaseous fuels even over a wide area is easy through the pipe lines and as such handling of the fuel is altogether eliminated. Gaseous fuels give economy of heat and produce higher temperatures as they can be preheated in regenerative furnaces and thus heat from hot flue gases can be recovered.

Important properties of gaseous fuels :

1. Heating value or calorific value.
2. Viscosity.
3. Specific gravity.
4. Density.
5. Diffusibility.

Typical composition of some gaseous fuels is given below :

Fuel	H_2	CO	CH_4	C_2H_4	C_2H_6	C_4H_8	O_2	CO_2	N_2
Natural gas	—	1	93	—	3	—	—	—	3
Coal gas	53.6	9.0	25	—	—	3	0.4	3	6
Blast furnace gas	2	27	—	—	—	—	—	11	—

1.3.1.4. Calorific or heating values of fuels

The **calorific value** *of the fuel is defined as the energy liberated by the complete oxidation of a unit mass or volume of a fuel.* It is expressed in kJ/kg for solid and liquid fuels and kJ/m^3 for gases.

Fuels which contain hydrogen have two calorific values, the *higher* and the *lower*. The *'lower calorific value'* is the heat liberated per kg of fuel after deducting the heat necessary to vaporise the steam, formed from hydrogen. The *'higher or gross calorific value' of the fuel is one indicated by a constant-volume calorimeter in which the steam is condensed and the heat of vapour is recovered.*

The lower or net calorific value is obtained by subtracting latent heat of water vapour from gross calorific value. In other words, the relation between Lower Calorific Value (L.C.V.) and Higher Calorific Value (H.C.V.) can be expressed in the following way :

$$\text{L.C.V.} = (\text{H.C.V.} - 2465\, m_w) \qquad ...(1.1)$$

where m_w is the mass of water vapour produced by combustion of 1 kg of fuel and 2465 kJ/kg is the latent heat corresponding to standard temperature (saturation) of 15°C.

In MKS units:

$$\text{L. C. V.} = (\text{H. C. V.} - 588.76\, m_w)$$

where m_w is the mass of water vapour produced by combustion of 1 kg of fuel and 588.76 is the latent heat value in kcal as read from steam tables for 1 kg of water vapour

Dulong's formula (Solid/liquid fules). Dulong suggested a formula for the calculation of the calorific value of the solid or liquid fuels from their chemical composition which is as given below :

Gross calorific value,

$$\text{H.C.V.} = \frac{1}{100}\left[33800\,\text{C} + 144000\left(\text{H} - \frac{\text{O}}{8}\right) + 9270\,\text{S}\right] \text{ kJ/kg} \qquad ...(1.2)$$

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$$\left[\text{In MKS units: } \text{H.C.V.} = \frac{1}{100}\left[8080\,\text{C} + 34500\left(\text{H} - \frac{\text{O}}{8}\right) + 2240\,\text{S kcal / kg}\right]\right]$$

where C, H, O and S are carbon, hydrogen, oxygen and sulphur in percentages respectively in 100 kg of fuel. In the above formula, the oxygen is assumed to be in combination with hydrogen and only extra surplus hydrogen supplies the necessary heat.

1.3.2. Energy Stored in Water

- The energy contained in flowing streams of water is a form of mechanical energy. It may exist as the kinetic energy of a moving stream or as potential energy of water at some elevation with respect to a lower datum level, an example of which would be the water held behind a dam. *Hydraulic plants* are slowly increasing in number, although the number of new plants of this type built is quite small compared with those which exploit heat energy. As a usual thing, the most desirable hydroelectric sites are the first to be utilized, consequently, as more hydroelectric plants are built, the owners must pay increasingly higher development costs.
- From the stand point of capitalistic economics, it is often hard to justify the development of hydroelectric power in comparison with steam power, but from the stand point of the conservation of a fixed natural resource, namely, its mineral fuels, it is obvious that every effort should be made to harness the water power of the country, since if unharnessed it goes to waste, whereas fuel, if unmined, remains intact and undiminished in value in the ground.
- Water power is quite cheap where water is available in abundance. Although *capital cost of hydroelectric power plants is higher as compared to other types of power plants yet their operating costs are quite low.*

1.3.3. Nuclear Energy

- One of the outstanding facts about nuclear power is the *large amount of energy that can be released from a small mass of active material.* Complete fission of one kg of uranium contains the energy equivalent of 4500 tonnes of coal or 2000 tonnes of oil. The *nuclear power is not only available in abundance but it is cheaper than the power generated by conventional sources.*

  The following factors go in *favour of nuclear energy :*

  (*i*) Practically independent of geographical factors.

  (*ii*) No combustion products.

  (*iii*) Clean source of power which does not contribute to air pollution.

  (*iv*) Fuel transportation networks and large storage facilities not required.
- The economic advantage of nuclear power can be realised only if one can ensure a guaranteed base load of about 75%. The number of electro-chemical processes (fertiliser plants), desalination of water and use of electricity for pumping water from tube wells assure a constant base load. Therefore, such type of power requirements must be developed before the adoption of nuclear power in the country.

1.3.4. Wind Power

- The man has been served by the power from winds for many centuries but the total amount of energy generated in this manner is *small.* The expense of installation and variability of operation have tended to *limit* the use of the windmill to intermittent services where *its variable output has no serious disadvantage.* The principal services of this nature are the *pumping of water into storage tanks and the charging of storage batteries.*

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- Windmill power equipment may be *classified* as follows :
  1. *The multi-bladed turbine wheel.* This is the foremost type in use and its efficiency is about 10 per cent of the kinetic energy of the wind passing through it.
  2. *The high-speed propeller type.*
  3. *The rotor.*
- The propeller and rotor types are *suitable for the generation of electrical energy,* as both of them possess the ability to start in very low winds. The *Propeller type is more likely to be used in small units* such as the driving of small battery charging generators, whereas the *rotor,* which is rarely seen, is more practical *for large installations,* even of several hundred kilowatts' capacity.
- In india, the wind velocity along coastline has a range 10-16 kmph and a survey of wind power has revealed that wind power is capable of exploitation for pumping water from deep wells or for generating small amounts of electric energy.

Modern windmills are capable of working on velocities as low as 3-7 kmph while *maximum efficiency is attained at 10-12 kmph.*

- A normal working life of 20 to 25 years is estimated for windmills.
- The great advantage of this source of energy is that *no operator is needed and no maintenance and repairs are necessary for long intervals.*

Characteristics of wind power/energy. Some characteristics of wind energy are given below :

1. No fuel provision and transport are required in wind energy systems.
2. It is a renewable source of energy.
3. Wind power systems are non-polluting.
4. Wind power systems, upto a few kW, are less costly, but on a large scale, costs can be competitive with conventional electricity. Lower costs can be achieved by mass production.

Problems associated with wind energy :

1. Wind energy systems are *noisy in operation.*
2. *Large areas* are needed to install *wind farms* for electrical power generators.
3. Wind energy available is *dilute and fluctuating in nature.* Because of dilute form, conversion machines have to be necessarily large.
4. Wind energy *needs storage means* because of its irregularity.

1.3.5. Solar Energy

- A lot of work to utilise solar energy for generation of steam has been done in some countries, and it is likely that this could be developed on commercial scale.
- A serious fault of this source of energy is, of course, that it is *effective only during the day,* so that if a continuous output is needed, some large reservoir of energy, such as a storage battery or a heat accumulator tank, must be drawn upon at night. Also, the output is handicapped if there is cloudy weather. Nevertheless, there are some locations in the world where strong solar radiation is received very regularly, and where the sources of mineral fuel are either scanty or entirely lacking. Such locations offer more interest to the solar power plant builder than the more favoured regions of earth.
- For developing solar energy two ways have been explored *viz.,* the *glass lens and the reflector.* These devices concentrate the solar rays to a focal point which is characterised by a high degree of heat which can be utilised to boil water and generate steam. The reflector is the better of the two methods due to the convenience with which it can be

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manufactured in different shapes and sizes. If an arrangement is provided to turn the reflector with the sun, so that the rays can constantly concentrate at the focal point, a continuous supply of heat is made available during the hours of the day. However, a great deal of practical research is still necessary before the solar energy can be *commercially exploited at a cheaper rate.*

- Conditions for utilisation of solar energy, in India, are favourable since for nearly six months of the year sunshine is uninterrupted during the day, while in the other six months cloudy weather and rain provide conditions suitable for water power. Thus, a *coordination of solar energy with water power can provide a workable plan for most places in India.*

1.3.6. Tidal Power

- The rise and fall of tides offers a means for storing water at the rise and discharging the same at fall. Of course the head of water available under such cases is very low but with increased catchment area considerable amounts of power can be generated at a negligible cost.

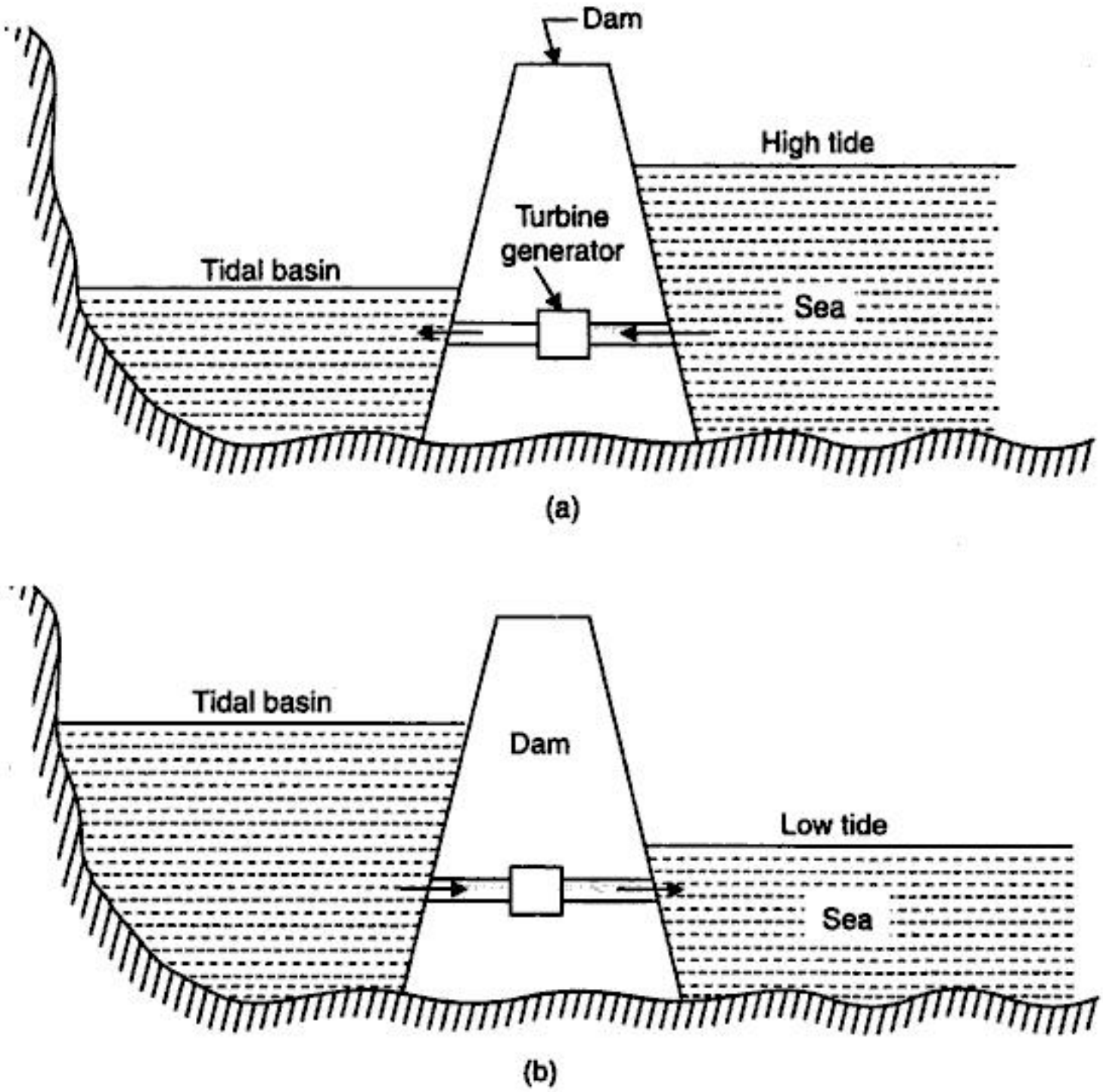

Fig. 1.1. Generation of power by tides.

- The use of tides for electric power generation is practical in a few favourably situated sites where the geography of an inlet of bay favours the construction of a large scale

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hydroelectric plant. To harness the tides, a dam would be built across the mouth of the bay in which large gates and low head hydraulic turbines would be installed. At the time of high tide the gates are opened and after storing water in the tidal basin the gates are closed. After the tide has recided, there is a working hydraulic head between the basin water and open sea/ocean and the water is allowed to flow back to the sea through water turbines installed in the dam. With this type of arrangement, the generation of electric power is *not continuous*. However by using reversible water turbine the turbine can be run continuously as shown in Fig. 1.1.

1.3.7. Geothermal Energy

In many places on the earth natural steam escapes from surface vents. Such natural steam wells suggest the possibility of tapping terrestrial heat (or geothermal energy) in this form and using it for the development of power. Unfortunately, the locations where the steam-producing substrata seem to be fairly close to the surface are far removed from centres of civilization where the power could be usefully employed. Nevertheless, there are probably many places where, although no natural steam vent or hot springs are showing, deep drillings might tap a source of underground steam. The cost of such explorations and the great likelihood of an unsuccessful conclusion are not very conductive to exploitation of this source of energy.

There are two ways of electric power production from geothermal energy :

(*i*) Heat energy is transferred to a working fluid which operates the power cycle. This may be particularly useful at places of fresh volcanic activity where the molten interior mass of earth vents to the surface through fissures and substantially high temperatures, such as between 450 to 550°C can be found. By embedding coil of pipes and sending water through them steam can be raised.

(*ii*) The hot geothermal water and/or steam is used to operate the turbines directly. From the well-head the steam is transmitted by pipelines upto 1 m in diameter over distances upto about 3 km to the power station. Water separators are usually employed to separate moisture and solid particles from steam.

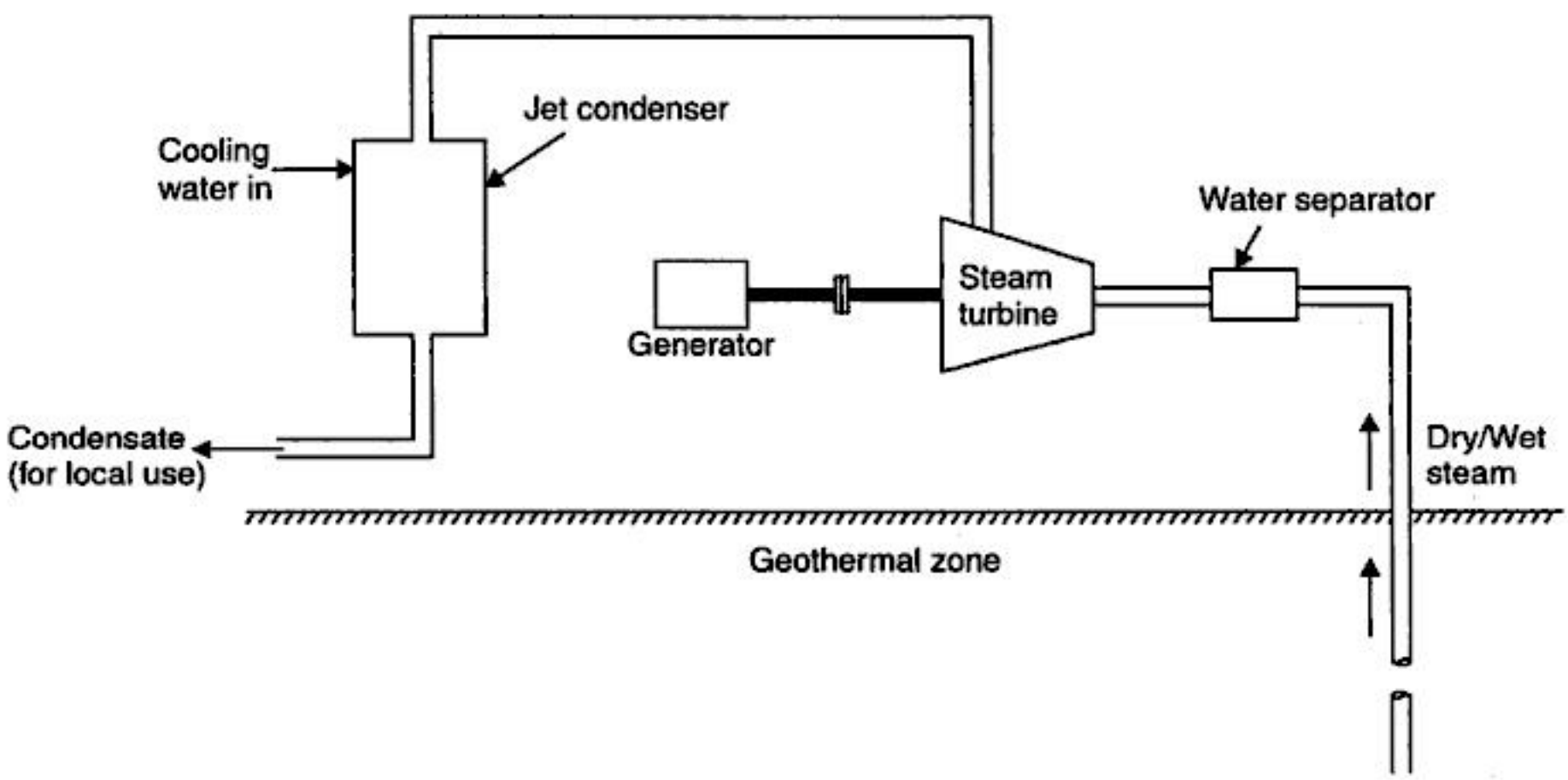

Fig. 1.2. Geothermal power plant.

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Presently, only steam coming out of the ground is used to generate electricity, the hot water is discarded, because it contains as much as 30% dissolved salts and minerals, and these cause serious rust damage to the turbine. The water, however, contains more than $\frac{1}{3}$rd of the available thermal energy.

1.3.8. Thermo-electric Power

According to *Seebeck effect*, when the two ends of a loop of two dissimilar metals are held at different temperatures, an electromotive force is developed and the current flows in loop. This method, by selection of suitable materials, can also be used for power generation. This method involves *low initial cost* and *negligible operating cost.*

1.4. POWER SYSTEMS' STRUCTURE

- The main components of an electric power system are :
  (*i*) *Generating stations.*
  (*ii*) *Transmission systems.*
  (*iii*) *Distributon systems.*
  - — Generating stations and a distribution system are connected through transmission lines, which also connect one power system (grid, area) to another.
  - — A distribution system connects all the loads in a particular area to the transmission lines.
- Individual power systems, for economical and technological reasons, are organised in the form of electrically connected areas or ***regional grids*** (also called ***power pools***). Each area or regional grid operates technically and economically independently but these are eventually interconnected (*Interconnection* has the *economic advantage of reducing the reserve generation capacity in each area*) to form a *national grid* (which may even form an *international grid*) *so that each area is contractually tied to other areas in respect to certain generation and scheduling features.*
- *Electric power* is generated at a *voltage of 11 to 25 kV which then is stepped up to the transmission levels in the range of 6 to 400 kV (or higher).*
  - — As the transmission capability of a line is *proportional to the square of its voltage,* research is continuously being carried out to raise transmission voltages. Some of the countries are already employing 765 kV.
  - — In India, several 400 kV lines are already in operation.
  - — In the near future the voltages are expected to rise to 1200 kV.
- It is *economical to transmit bulk power by D.C. transmission for very long distances, over 600 km.* The D.C. voltages used are 400 kV and above, and the line is connected to the A.C. systems at the two ends through a transformer and converting/inverting equipment.
  - — The first HVDC transmission line has already been commissioned and several others are being planned.
- Depending upon the transmission line voltage, the *first stepdown* of the voltage from transmission level is at the bulk power station, where the reduction is to a *range of 33 to 132 kV* (Some industries may require power at these voltage levels and this stepdown is from the transmission and grid level to subtransmission level). In the *next stepdown* in voltage, at the distribution substation, two distribution voltage levels, normally employed are :
  - — The primary or feeder voltage —11 kV.
  - — The secondary or consumer voltage —415 V (3-phase)/230 V (1-phase)

  In the chapters to follow, different types of generating stations will be discussed.

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HIGHLIGHTS

1. Energy appears in many forms, but has one thing in common—energy is possessed of the ability to produce a dynamic, vital effect.
2. Sources of energy are :
   (*i*) Fuels (*ii*) Energy stored in water (*iii*) Nuclear energy
   (*iv*) Wind power (*v*) Solar energy (*vi*) Tidal power
   (*vii*) Geothermal energy (*viii*) Thermoelectric power.
3. A chemical fuel is a substance which releases heat energy on combustion. The principal element of each fuel are carbon and hydrogen. Though sulphur is a combustible element too but its presence in the fuel is considered to be undesirable.
4. The principal types of power plants are :
   (*i*) Steam plants using coal, oil or nuclear fission (*ii*) Internal combustion engine plants
   (*iii*) Gas turbine plants (*iv*) Hydro-electric plants.
5. The main components of an electric power system are :
   (*i*) Generating stations ; (*ii*) Transmission systems ; (*iii*) Distribution systems.

THEORETICAL QUESTIONS

1. Enumerate sources of energy.
2. What is a chemical fuel ? How does it differ from a nuclear fuel ?
3. How are chemical fuels classified ?
4. Explain briefly the following solid fuels :
   Lignites and brown coals, bituminous coal, and coke.
5. List the advantages of liquid fuels.
6. Describe the following gaseous fuels :
   Coal gas, Coke-oven gas, Blast furnace gas and Producer gas.
7. What are the advantages of gaseous fuels ?
8. State the factors which go in favour of nuclear energy.
9. Write short notes on :
   Tidal power, wind power and thermoelectric power.
10. Name the principal types of power plants.
11. Why do we feel the necessity of using excess air for burning fuels ?
12. How can the following be calculated ?
    (*i*) Weight of carbon in flue gases.
    (*ii*) Weight of flue gas per kg of fuel burnt.

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2

Steam Power Plant

2.1. **Introduction.** 2.2. **Classification of steam power plants.** 2.3. **Layout of a modern steam power plant.** 2.4. **Essential requirements of steam power station design.** 2.5. **Selection of site for steam power station.** 2.6. **Capacity of steam power plant.** 2.7. **Choice of steam conditions.** 2.8. **Fuel handling** : Introduction—requirements of good coal handling plant—coal handling systems—coal handling—layout of a fuel handling equipment. 2.9. **Combustion equipment for steam boilers** : General aspects—combustion equipment for solid fuels—selection considerations—burning of coal—stoker firing, pulverised fuel firing—pulverised fuel burners—oil burners—gas burners. 2.10. **Fluidised Bed Combustion (FBC).** 2.11. **Ash handling** : Ash handling equipment—ash handling systems. 2.12. **Dust collection** : Introduction, removal of smoke, removal of dust and dust collectors— uses of ash and dust—general layout of ash handling and dust collection system. 2.13. **Boilers** : Introduction—classification of boilers—comparison between 'fire tube and water tube' boilers—high pressure boilers. 2.14. **Steam turbines** : Introduction—classification of steam turbines—advantages of steam turbine over the steam engines—description of common types of turbines—methods of reducing wheel or rotor speed— difference between impulse and reaction turbines—steam turbine governing and control. 2.15. **Steam condensers** : Introduction—vacuum—organs of a steam condensing plant—classification of condensers—jet condensers—surface condensers—comparison between jet and surface condensers. 2.16. **Feed water treatment** : Classification of impurities in water—troubles caused by the impurities in water—methods of feed water treatment. 2.17. **Advantages and disadvantages of steam power plants.** 2.18. **Miscellaneous** : Useful life of steam power plant components—steam power plant pumps—cost of steam power plant—comparison of various types of power plants—thermal power stations in India. Highlights—Theoretical Questions.

2.1. INTRODUCTION

A **steam power plant** *converts the chemical energy of the fossil fuels (coal, oil, gas) into mechanical / electrical energy.* This is achieved by raising the steam in the boilers, expanding it through the turbines and coupling the turbines to the generators which convert mechanical energy to electrical energy as shown in Fig. 2.1.

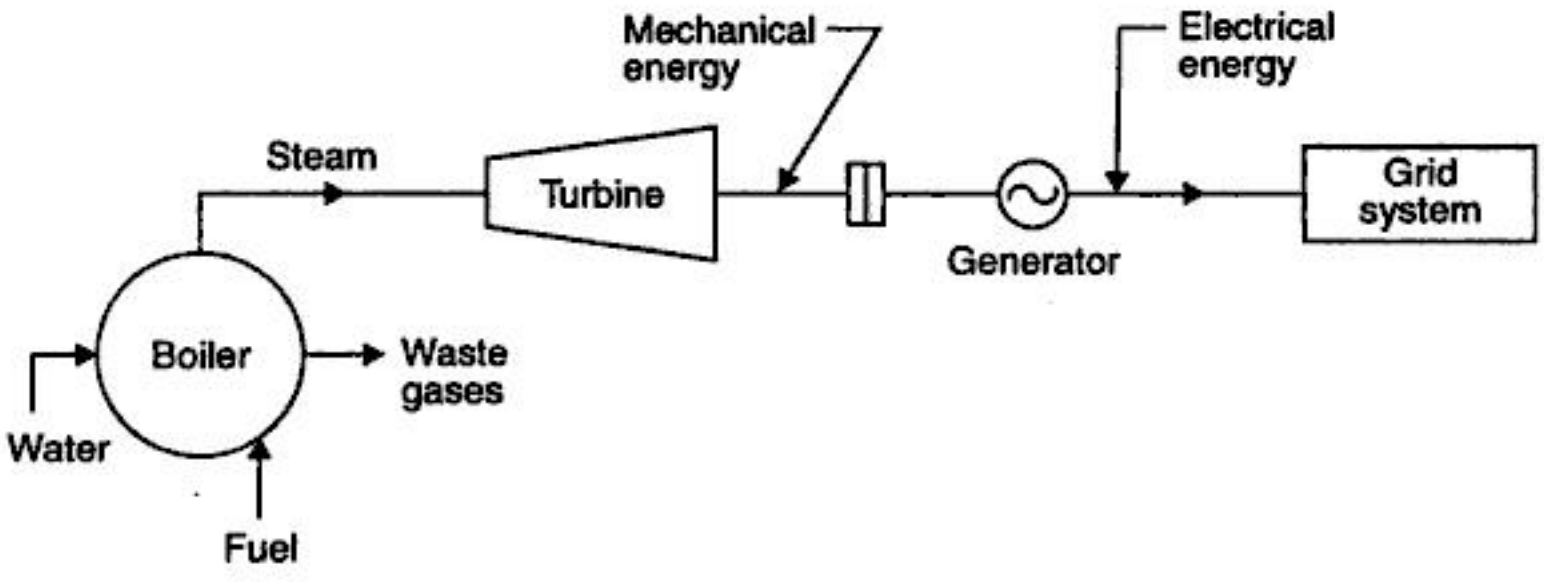

Fig. 2.1. Production of electric energy by steam power plant.

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The following two purposes can be served by a steam power plant :

1. To produce electric power.

2. To produce steam for industrial purposes besides producing electric power. The steam may be used for varying purposes in the industries such as *textiles, food manufacture, paper mills, sugar mills* and *refineries* etc.

2.2. CLASSIFICATION OF STEAM POWER PLANTS

The steam power plants may be *classified* as follows :

1. Central stations.

2. Industrial power stations or captive power stations.

1. **Central stations.** The electrical energy available from these stations is meant for general sale to the customers who wish to purchase it. Generally, these stations are *condensing type* where the exhaust steam is discharged into a condenser instead of into the atmosphere. In the condenser the pressure is maintained below the atmospheric pressure and the exhaust steam is condensed.

2. **Industrial power stations or captive power stations.** This type of power station is run by a manufacturing company for its own use and its output is not available for general sale. Normally these plants are *non-condensing* because a large quantity of steam (low pressure) is required for different manufacturing operations.

In the *condensing steam power plants* the following *advantages* accrue :

(*i*) The amount of energy extracted per kg of steam is *increased* (a given size of the engine or turbine develops more power).

(*ii*) The steam which has been condensed into water in the condenser, can be recirculated to the boilers with the help of pumps.

In non-condensing steam power plants a continuous supply of fresh feed water is required which becomes a problem at places where there is a shortage of pure water.

2.3. LAYOUT OF A MODERN STEAM POWER PLANT

Refer Fig. 2.2. The layout of a modern steam power plant comprises of the following *four circuits* :

1. Coal and ash circuit.

2. Air and gas circuit.

3. Feed water and steam flow circuit.

4. Cooling water circuit.

The brief description of these circuits is given below :

1. **Coal and ash circuit.** Coal arrives at the storage yard and after necessary handling, passes on to the furnaces through the *fuel feeding device.* Ash resulting from combustion of coal collects at the back of the boiler and is removed to the ash storage yard through *ash handling equipment.*

2. **Air and gas circuit.** Air is taken in from atmosphere through the action of a forced or induced draught fan and passes on to the furnace through the *air preheater*, where it has been heated by the heat of flue gases which pass to the chimney *via* the preheater. The flue gases after passing around boiler tubes and superheater tubes in the furnace pass through a *dust* catching device or precipitator, then through the economiser, and finally through the air preheater before being exhausted to the atmosphere.

3. **Feed water and steam flow circuit.** In the water and steam circuit condensate leaving the condenser is first heated in a closed feed water heater through extracted steam from the lowest pressure extraction point of the turbine. It then passes through the *deaerator* and a few more water heaters before going into the boiler through *economiser.*

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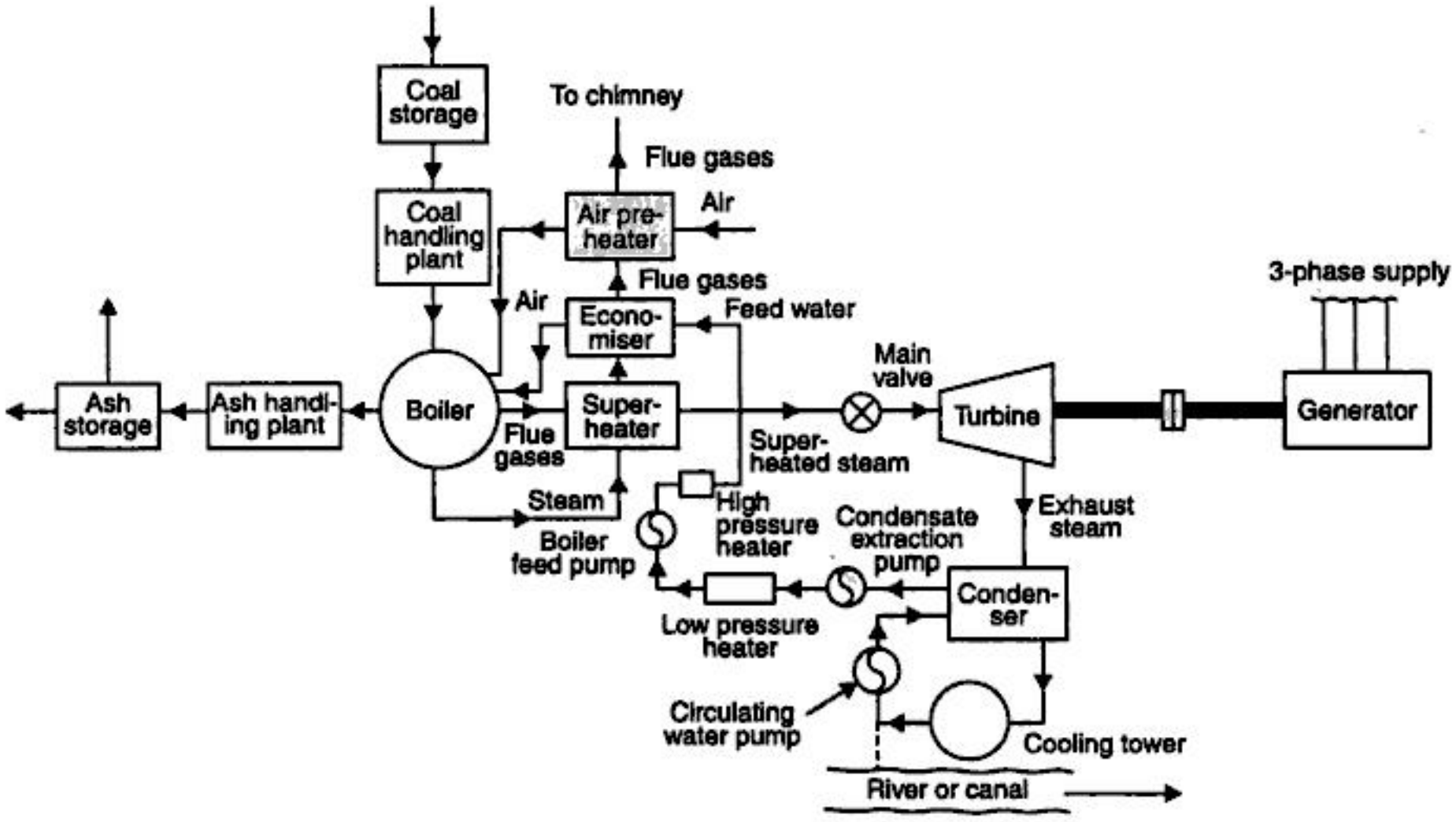

Fig. 2.2. Layout of a steam power plant.

In the boiler drum and tubes, water circulates due to the difference between the density of water in the lower temperature and the higher temperature sections of the boiler. Wet steam from the drum is further heated up in the superheater before being supplied to the primemover. After expanding in high pressure turbine steam is taken to the reheat boiler and brought to its original dryness or superheat before being passed on to the low pressure turbine. From there it is exhausted through the condenser into the hot well. The condensate is heated in the feed heaters using the steam trapped (bled steam) from different points of turbine.

A part of steam and water is lost while passing through different components and this is compensated by supplying additional feed water. This feed water should be purified before hand, to avoid the scaling of the tubes of the boiler.

4. **Cooling water circuit.** The cooling water supply to the condenser helps in maintaining a low pressure in it. The water may be taken from a natural source such as river, lake or sea or the same water may be cooled and circulated over again. In the later case the cooling arrangement is made through spray pond or cooling tower.

Components of a Modern Steam Power Plant :

A modern steam power plant consists of the following *components :*

1. Boiler
   - (*i*) Superheater
   - (*ii*) Reheater
   - (*iii*) Economiser
   - (*iv*) Air-heater
2. Steam turbine
3. Generator
4. Condenser
5. Cooling towers
6. Circulating water pump
7. Boiler feed pump
8. Wagon tippler
9. Crusher house
10. Coal mill
11. Induced draught fans
12. Ash precipitators
13. Boiler chimney

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14. Forced draught fans
15. Water treatment plant
16. Control room
17. Switch yard.

2.4. ESSENTIAL REQUIREMENTS OF STEAM POWER STATION DESIGN

The *essential requirements of steam power station design are* :

1. Reliability.
2. Minimum capital cost.
3. Minimum operating and maintenance cost.
4. Capacity to meet peak load effectively.
5. Minimum losses of energy in transmission.
6. Low cost of energy supplied to the consumers.
7. Reserve capacity to meet future demands.

The above essential requirements depend to a large extent on the following :

(*i*) Simplicity of design.
(*ii*) Subdivision of plant and apparatus.
(*iii*) Use of automatic equipment.
(*iv*) Extensibility.

2.5. SELECTION OF SITE FOR STEAM POWER STATION

The following points should be taken into consideration while *selecting the site* for a steam power station :

1. Availability of raw material.
2. Nature of land.
3. Cost of land.
4. Availability of water.
5. Transport facilities.
6. Ash disposal facilities.
7. Availability of labour.
8. Size of the plant.
9. Load centre.
10. Public problems.
11. Future extensions.

1. **Availability of raw material.** Modern steam power stations using coal or oil as fuel require huge quantity of it per annum. A thermal power plant of 400 MW capacity requires 5000 to 6000 tonnes of coal per day. Therefore, it is necessary to locate the plant as far as possible near the coalfields in order to save the transportation charges. Besides transportation charges, a plant located away from the coalfields, cannot always depend on the coal deliveries in time (*i*) as there may be failure of transportation system, (*ii*) there may be strike etc. at the mines. For these reasons a considerable amount of coal must be stored at the power stations, this results in :

(*i*) increased investment ;

(*ii*) increased space required at the site of the plant for the storage ;

(*iii*) losses in storage ; and

(*iv*) additional staff requirement.

If it is not possible to locate the plant near the coalfields then the plant should be located as near the railway station as possible. Even if this is not possible then at least arrangement should be made for railway siding to the power plant so that the coal wagons can be shunted from the station to the site of power plant. This applies to plants using oil as fuel, as well.

2. **Nature of land.** The type of the land to be selected should have *good bearing capacity* as it has to withstand the *dead load* of the plant and the *forces transmitted to the foundation* due to the machine operations. The minimum bearing capacity of the land should be 1 MN/m^2.

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3. **Cost of land.** Considerable area is required for the power stations. The cost of the land for that purpose should be reasonable. The large plants in the heart of big cities and near the load centre are not economical as the cost of land is very high.

4. **Availability of water.** Steam power stations use water as the working fluid which is repeatedly evaporated and condensed. Theoretically there should be no loss of water, but in fact some make up water is required. Besides this, considerable amount of water is required for condensers. A large quantity of water is also required for disposing the ash if hydraulic system is used. It is, therefore, necessary to locate the power plant near the water source which will be able to supply the required quantity of water throughout the year.

5. **Transport facilities.** Availability of proper transport facilities is another important consideration in locating the thermal power station. It is always necessary to have a railway line available near the power station for bringing in heavy machinery for installation and for bringing the fuel.

6. **Ash disposal facilities.** The ash handling problem is more serious than coal handling because it comes out in hot condition and it is highly corrosive. Its effect on atmospheric pollution are more serious as the human health is concerned. Therefore, there must be sufficient space to dispose of large quantity of ash.

In a power station of 400 MW capacity 10 hectares area is required per year if the ash is dumped to a height of 6.5 metres.

7. **Availability of labour.** During construction of plant enough labour is required. The labour should be available at the proposed site at cheap rate.

8. **Size of the plant.** The expenses involved in electric transmission from a *small plant* are *relatively severe*, owing to the impracticability of using high voltages, so that the electric transmission feature alone becomes dominant in the location of the plant. It case of *large plants*, the costs of transporting enormous quantities of coal and water are considerably high ; therefore, the plant must be located near the pit head provided the required water quantity must be available as near as possible. The large plants should be located close to the railroad offering adequate services. The economic significance of the large plant with small one is much greater than the mere ratio of size.

9. **Load centre.** A power station must be located *near the loads* to which it is supplying power. However, a plant cannot be located near all loads. As such C.G. of the loads is determined with reference to two arbitrarily chosen axes, this C. G. is known as the *load centre* (see Fig. 2.3).

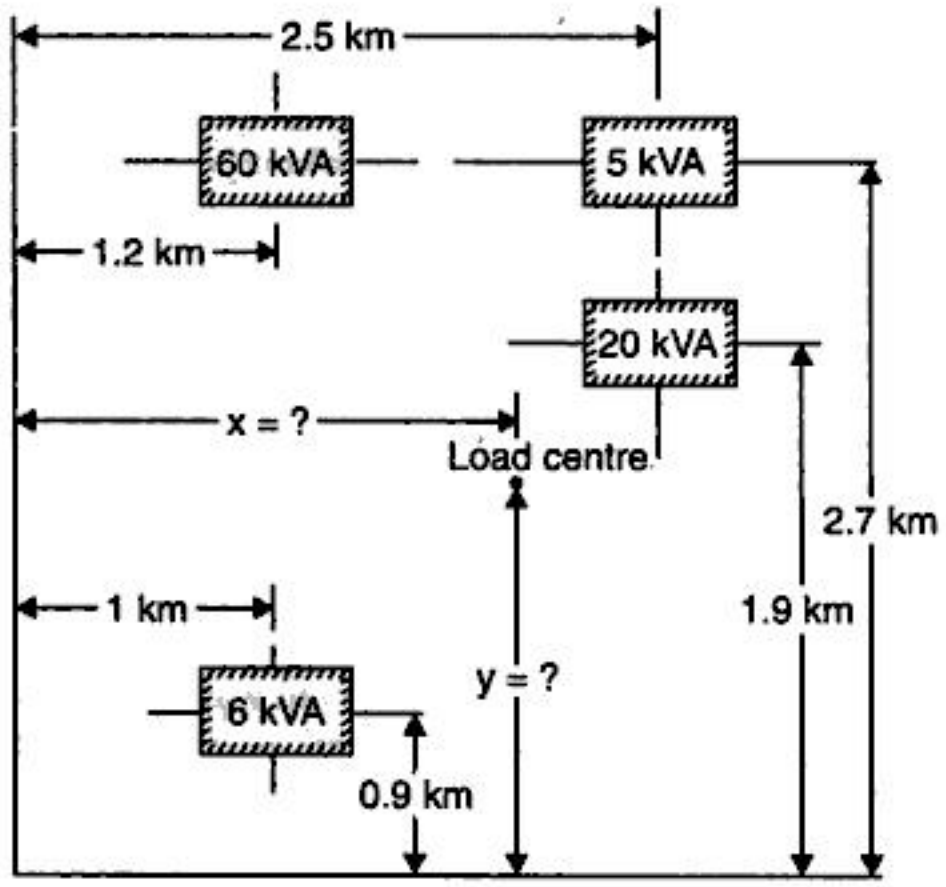

Fig. 2.3. Load centre.

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The power plant should be located, as far as possible near the load centre in order to *minimize the cost of transmission lines and also the losses occuring in them.*

10. **Public problems.** In order to avoid the nuisance from smoke, fly ash and heat discharged from the power plant, it should be located far away from the towns.

11. **Future extensions.** The choice of the site should allow for economical extensions consistent with the estimated growth of load.

12. Consent of Town Planning Department must be sought in case urban area is selected for the purpose.

2.6. CAPACITY OF STEAM POWER PLANT

The power plant capacity can be determined by studying *the load duration curve and the anticipated future demands. The minimum capacity of the plant must be equal to at least the peak load.*

(*i*) In case of "*Small loads*", it may be economical to install two units of equipment, each being capable of supplying the maximum demand independently. In the event of failure of one unit or during maintenance etc., at least one unit can be used to maintain uninterrupted supply of energy.

(*ii*) In case of "*medium power plants*", usually the number of units is more than two with the total installed capacity equal to the *maximum demand plus the capacity of two large units.*

(*iii*) "*Large power plants*" are generally *conservately rated.* In the case of steam turbines, there is an overload capacity of 10 to 15% of the rated capacity. With a number of units, peak load can be easily adjusted by overloading some units temporarily.

The power plant load can be reduced by dropping the supply voltage. Thus a 5 percent reduction in supply voltage results in similar reduction in the load. An electric supply undertaking has to maintain the voltage within 10 percent of the declared pressure as per Indian Electricity Act ; so *during peak hours the voltage can be reduced within the allowable limits in order to meet the demand without use of additional units.* By using this technique saving of capital cost is materialised.

When a new unit is to be added to the existing power station, its size is decided on the following considerations :

1. Effect of additional unit on the thermal efficiency of the plant.
2. Expected rate of increase of maximum demand over the next few years.
3. The room available for the additional unit.
4. The suitability of the generator to the existing system regarding temperature, pressure etc.

Rating of Units :

Normally the output of units is classified under the following heads :

(*i*) Economical rating.

(*ii*) Maximum continuous rating.

A generator need not operate most economically at full load. For the most economical operation, the present trend is towards economical running at 75-85 percent of full load.

Maximum continuous rating of a generating unit is the maximum load at which it can be run continuously for several hours. It is normally 10-15 percent less than the maximum capacity of the unit.

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2.7. CHOICE OF STEAM CONDITIONS

The choice of steam conditions depends upon the following *factors* :

1. Price of coal.
2. Capital cost of the plant.
3. Time available for erection.
4. Thermal efficiency obtainable.
5. The station 'load factor'.

The present trend is towards adoption of high pressures and high temperatures. The effect of increased pressure and temperature on the efficiency and cost of plant is illustrated with the help of Figs. 2.4 and 2.5. It is evident from the curves that :

(*i*) *With the increase in pressure the efficiency obeys the 'law of diminishing returns'.*

(*ii*) With the increase in temperature the efficiency obeys the '*straight line law*' indicating the desirability of adopting the highest possibe temperature. The strength of material available limits the adoption of high temperatures. Beyond 500°C there is a very rapid change in the physical properties of the material and the problem becomes complicated. *With the increase in pressures the degree of superheat should be decreased in order to keep the total temperature within limits.*

For entirely new stations, present practice favours the use of steam pressures around 60 bar, but there is a profitable field for higher pressures of the order of 100 bar, when the problem is that of *increasing thermal efficiency of existing medium pressure units.*

It may be noted that *consumption of steam per kilo-watt hour decreases with the increased pressure.*

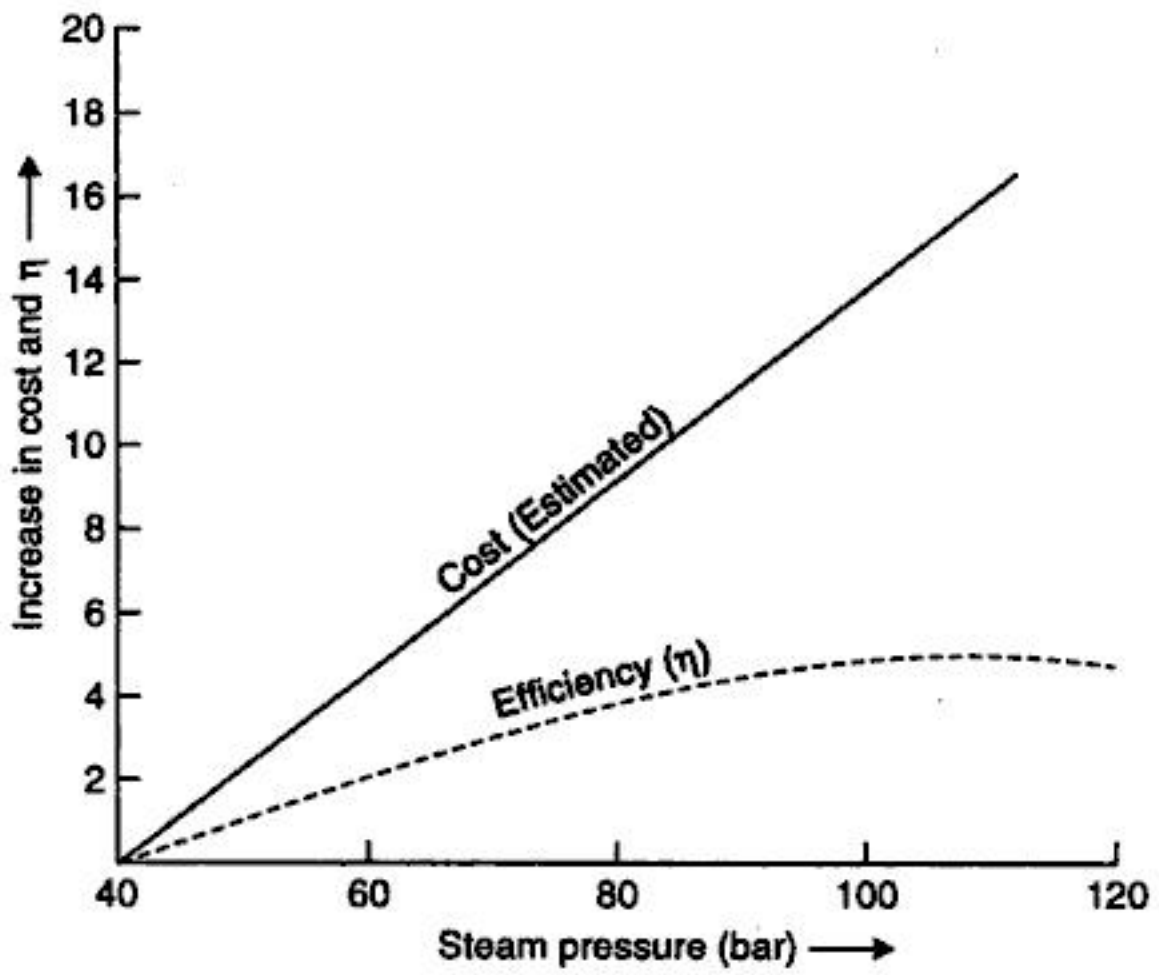

Fig. 2.4. Effect of steam pressure on cost and η (efficiency).

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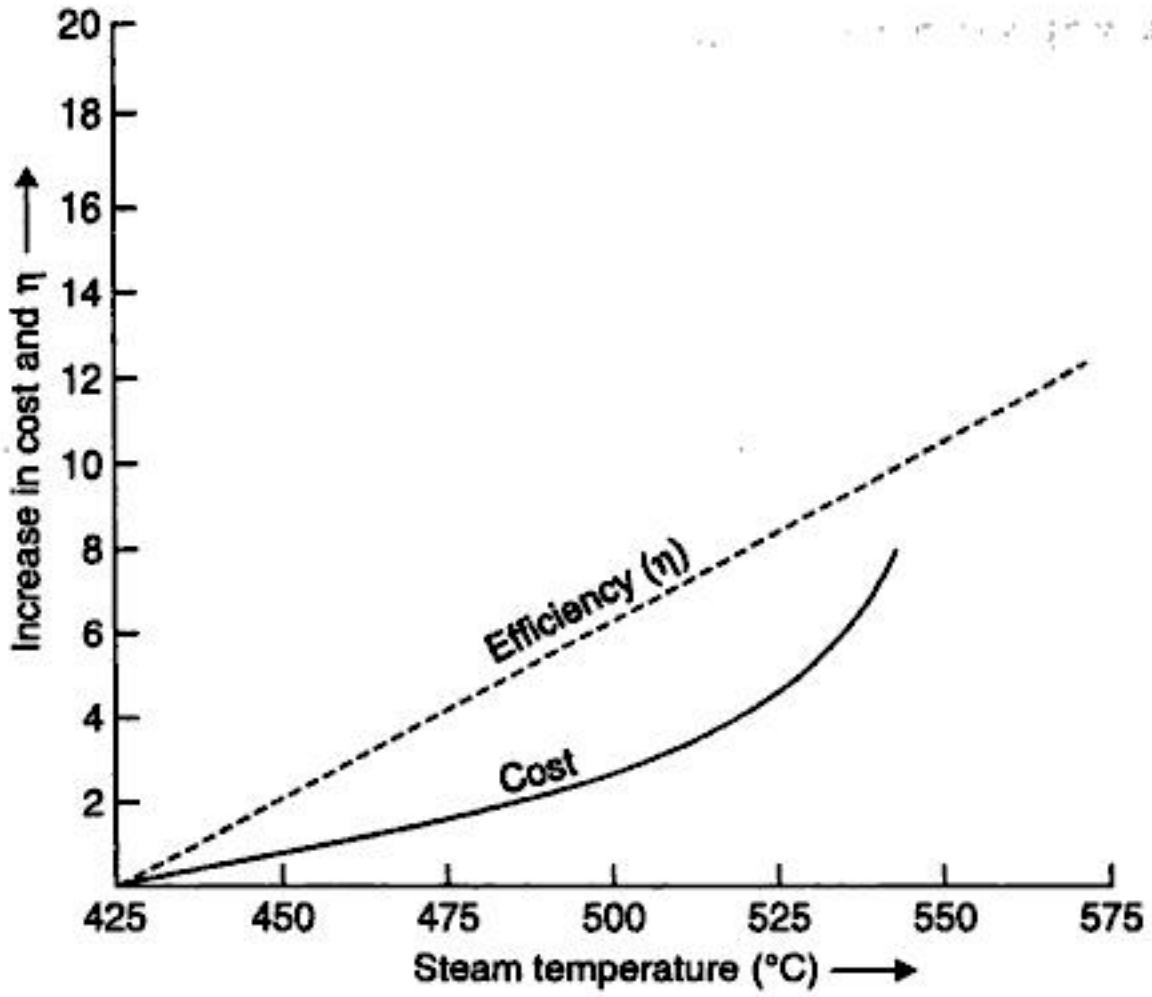

Fig. 2.5. Effect of steam temperature on cost and η (efficiency).

Fig. 2.6 shows that *as the average output of plant units increases the percentage total capital cost decreases.*

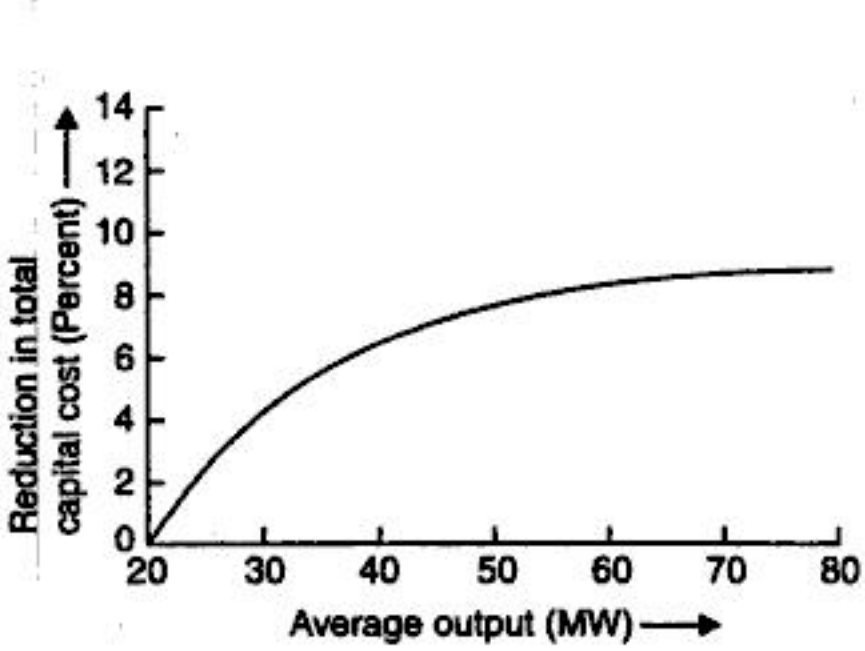

Fig. 2.6

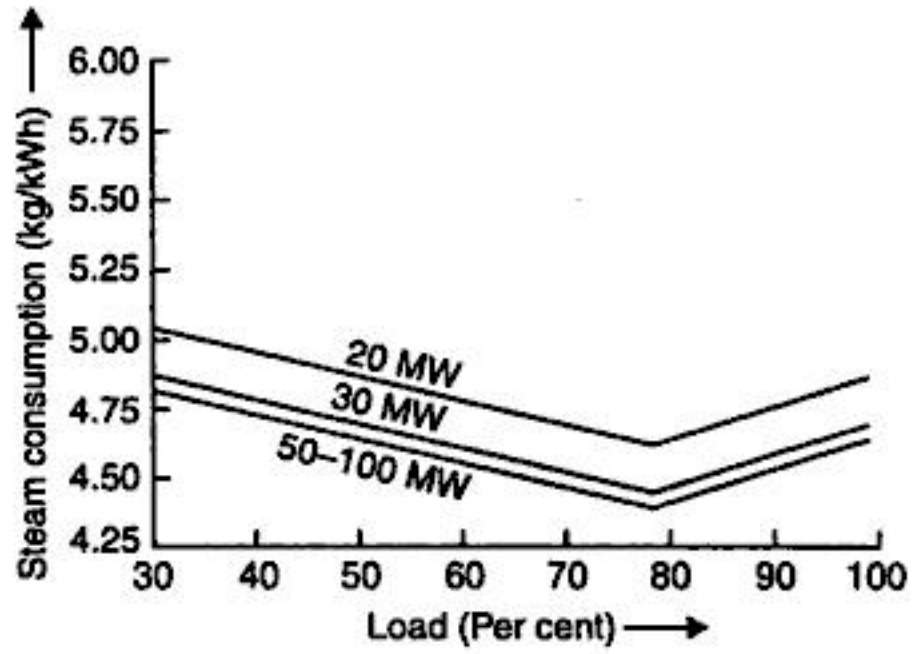

Fig. 2.7

Fig. 2.7 indicates that steam consumption decreases with increase in the capacity of the unit.

2.8. FUEL HANDLING

2.8.1. Introduction

Three types of fuels can be burnt in any type of steam generating plant : 1. Solid fuel such as *coal*, 2. Liquid fuel as oil, and 3. Gaseous fuel as gas. Supply of these fuels to the power plants from various sources is one of the important considerations for a power plant engineer. The handling of these fuels is an important aspect. The following *factors* should be considered in *selecting the fuel handling system* :

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1. Plant fuel rate.
2. Plant location in respect of fuel shipping.
3. Storage area available.

Fuel handling plant needs extra attention, while designing a thermal power station, as almost 50 to 60 percent of the total operating cost consists of fuel purchasing and handling. *Fuel system is designed in accordance with the type and nature of fuel.*

Continuously increasing demand for power at lower cost calls for setting up of higher capacity power stations. Rise in capacity of the plant poses a problem in coal supply system from coal mines to the power stations. The coal from coal mines may be transported by the following *means* :

1. Transportation by sea or river,
2. Transportation by rail,
3. Transportation by ropeways,
4. Transportation by road, and
5. Transportation of coal by pipeline.

The pipeline coal transport system offers the following *advantages* :

1. It provides simplicity in installation and increased safety in operation.
2. More economical than other modes of transport when dealing with large volume of coal over long distances.
3. This system is continuous as it remains unaffected by the vagaries of climate and weather.
4. High degree of reliability.
5. Loss of coal during transport due to theft and pilferage is totally eliminated.
6. Manpower requirement is low.

2.8.2. Requirements of Good Coal Handling Plant

1. It should need minimum maintenance.
2. It should be reliable.
3. It should be simple and sound.
4. It should require a minimum of operatives.
5. It should be able to deliver requisite quantity of coal at the destination during peak periods.
6. There should be minimum wear in running the equipment due to abrasive action of coal particles.

2.8.3. Coal Handling Systems

"*Mechanical handling*" of coal is preferred over "*manual handling*" due to the following *reasons* :

1. Higher reliability.
2. Less labour required.
3. Economical for medium and large capacity plants.
4. Operation is easy and smooth.
5. Can be easily started and can be economically adjusted according to the need.
6. With reduced labour, management and control of the plant becomes easy and smooth.
7. Minimum labour is put to unhealthy condition.
8. Losses in transport are minimised.

Disadvantages :

1. Needs continuous maintenance and repair.
2. Capital cost of the plant is increased.

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3. In mechanical handling some power generated is usually consumed, resulting in less net power available for supply to consumers.

2.8.4. Coal Handling

Refer to Fig. 2.8.

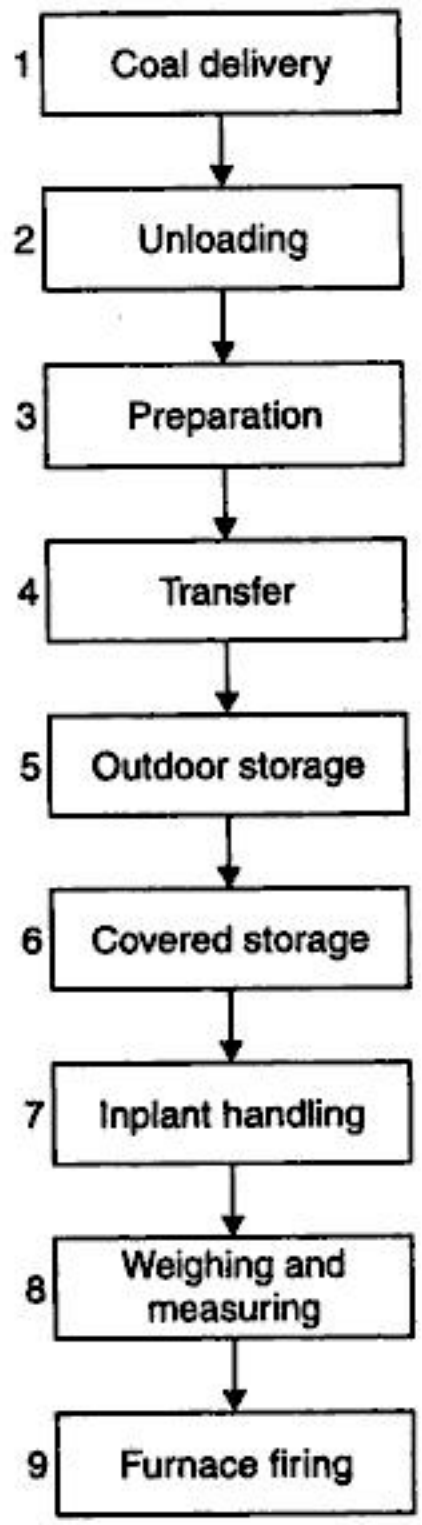

Fig. 2.8. Various stages in coal handling.

The following *stages / steps* are involved in handling the coal :

1. Coal delivery 2. Unloading 3. Preparation 4. Transfer
5. Storage of coal 6. In-plant handling 7. Weighing and measuring
8. Furnace firing.

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Fig. 2.9 shows the outline of coal handling equipment.

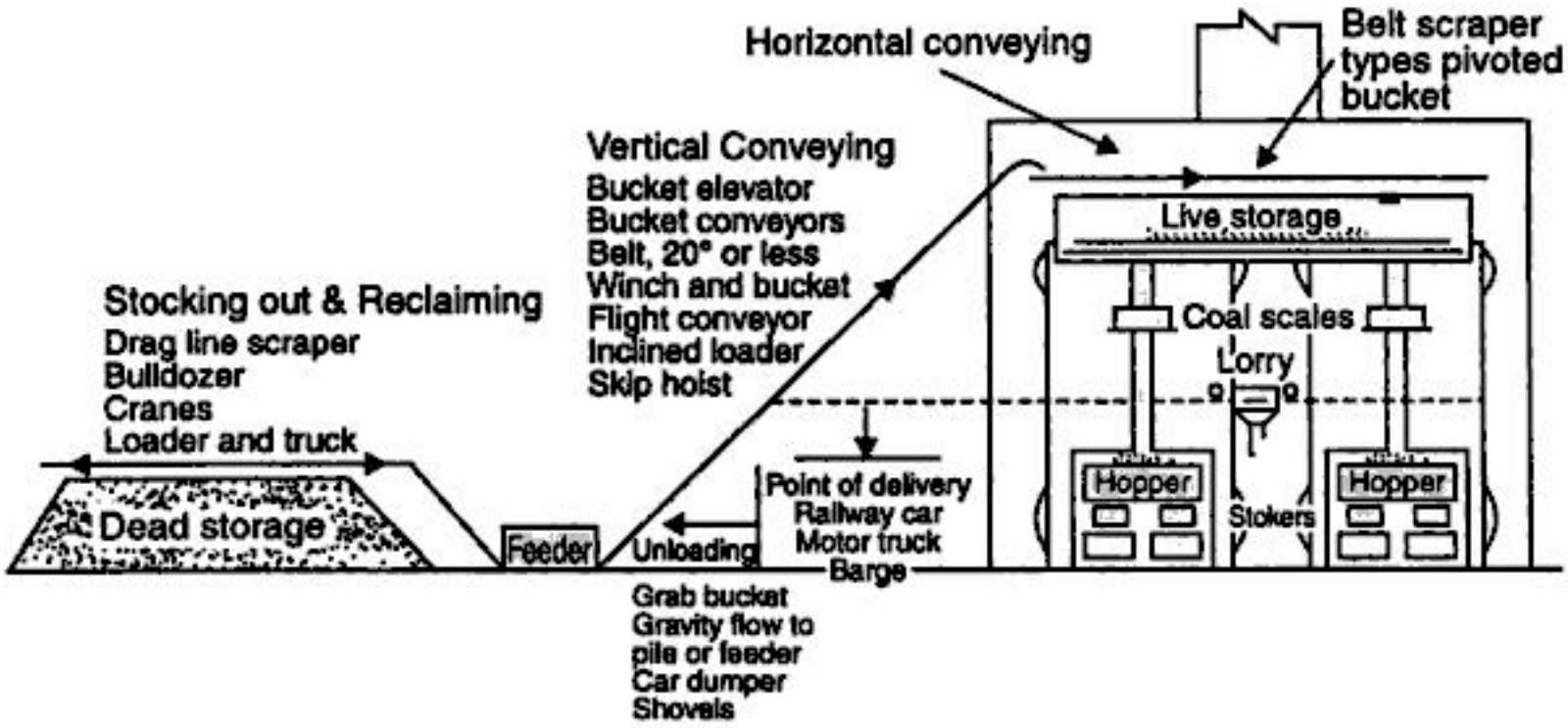

Fig. 2.9. Outline of coal handling equipment.

2.8.5. Layout of a Fuel Handling Equipment

Fig. 2.10 shows a schematic layout of a fuel handling equipment of a modern steam power plant where coal (a solid fuel) is used. Brief description is as follows :

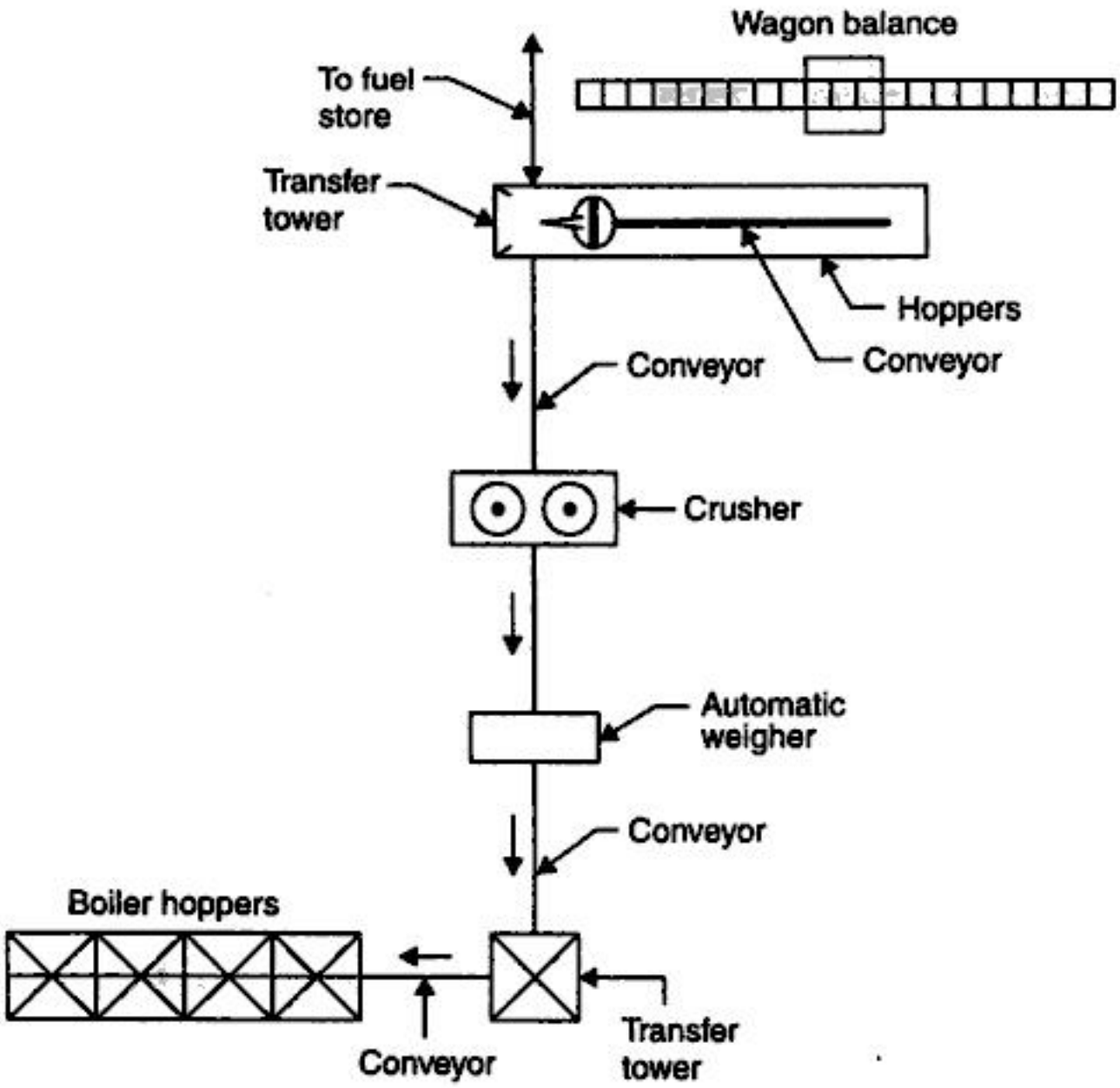

Fig. 2.10. Layout of a fuel handling equipment.

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— Coal is supplied to the power plant in railway wagons.
— After weighing on wagon balance the coal is then unloaded into underground hoppers or bunkers. The wagon can be unloaded either manually or through rotary wagon tipplers.
— From the bunkers, the coal is lifted by conveyor to the transfer tower from where it can be delivered either to the fuel store or by a conveyor to a crusher.
— The coal is then passed through the magnetic separators and screens and crushed in crushers into pieces 25 to 30 mm in size for stoker firing and 10 to 20 mm when pulverished fuel is fired in boiler furnaces. The crushed coal in the later case is *milled to a fine powder* and then it is carried through automatic weigher to a transfer tower where fuel is lifted and distributed between boiler hoppers by a conveyor.

2.9. COMBUSTION EQUIPMENT FOR STEAM BOILERS

2.9.1. General Aspects

The combustion equipment is a component of the steam generator. Since the source of heat is the combustion of a fuel, a working unit must have, whatever, equipment is necessary to receive the fuel and air, proportioned to each other and to the boiler steam demand, mix, ignite, and perform any other special combustion duties, such as distillation of volatile from coal prior to ignition.

- *Fluid fuels are handled by burners ; solid lump fuels* by *stokers.*
- In boiler plants hand firing on grates is *practically unheard* of nowdays in new plants, although there are many small industrial plants still in service with hand firing.
- The fuels are mainly bituminous coal, fuel oil and natural gas mentioned in order of importance. All are composed of hydrocarbons, and coal has, as well, much fixed carbon and little sulphur. To burn these fuels to the desired end products, CO_2 and H_2O, requires (*i*) *air in sufficient proportions,* (*ii*) *a good mixing of the fuel and air,* (*iii*) *a turbulence* or *relative motion between fuel and air.* The combustion equipment *must fulfill these requirements and, in addition, be capable of close regulation of rate of firing the fuel, for boilers which ordinarily operate on variable load.* Coal-firing equipment *must also have a means for holding and discharging the ash residue.*

The basic requirements of combustion equipment :

1. Thorough mixing of fuel and air.

2. Optimum fuel-air ratios leading to most complete combustion possible maintained over full load range.

3. Ready and accurate response of rate of fuel feed to load demand (usually as reflected in boiler steam pressure).

4. Continuous and reliable ignition of fuel.

5. Practical distillation of volatile components of coal.

6. Adequate control over point of formation and accumulation of ash, when coal is the fuel.

Natural gas is used as a boiler fuel in gas well regions where fuel is relatively cheap and coal sources comparatively distant. The transportation of natural gas over land to supply cities with domestic and industrial heat has made the gas in the well more valuable and the gas-fired steam generator more difficult to justify in comparison with coal, or fuel cost alone. Cleanliness and convenience in use are other criteria of selection, but more decisive in small plants in central power stations.

Transportation costs add less to the delivery price of oil than gas ; also fuel oil may be stored in tanks at a reasonable cost, whereas, gas cannot. Hence although fuel oil is usually more costly than coal per kg of steam generated, many operators select fuel oil burners rather than stokers because of the simplicity and cleanliness of storing and transporting the fuel from storage to burner.

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Depending on the type of combustion equipment, boilers may be *classified* as follows :

1. Solid fuels fired :

(*a*) Hand fired

(*b*) Stoker fired

(*i*) Overfeed stokers

(*ii*) Underfeed strokers.

(*c*) Pulverised fuel fired

(*i*) Unit system

(*ii*) Central system

(*iii*) Combination of (*i*) and (*ii*).

2. Liquid fuel fired :

(*a*) Injection system

(*b*) Evaporation system

(*c*) Combination of (*a*) and (*b*).

3. Gaseous fuel fired :

(*a*) Atmospheric pressure system

(*b*) High pressure system.

2.9.2. Combustion Equipment for Solid Fuels—Selection Considerations

While selecting combustion equipment for solid fuels the following *considerations* should be taken into account :

1. Initial cost of the equipment.
2. Sufficient combustion space and its ability to withstand high flame temperature.
3. Area of the grate (over which fuel burns)
4. Operating cost
5. Minimum smoke nuisance.
6. Flexibility of operation.
7. Arrangements for thorough mixing of air with fuel for efficient combustion.

2.9.3. Burning of Coal

The two most commonly used methods for the burning of coal are :

1. Stroker firing
2. Pulverised fuel firing.

The selection of one of the above methods depends upon the following *factors* :

(*i*) Characteristics of the coal available.

(*ii*) Capacity of the boiler unit.

(*iii*) Load fluctuations.

(*iv*) Station load factor.

(*v*) Reliability and efficiency of the various types of combustion equipment available.

2.9.3.1. Stoker Firing

*A "**stoker**" is a power operated fuel feeding mechanism and grate.*

Advantages of stoker firing :

1. A cheaper grade of fuel can be used.

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2. A higher efficiency attained.
3. A greater flexibility of operations assured.
4. Less smoke produced.
5. Generally less building space is necessary.
6. Can be used for small or large boiler units.
7. Very reliable, maintenance charges are reasonably low.
8. Practically immune from explosions.
9. Reduction in auxiliary plant.
10. Capital investment as compared to pulverised fuel system is less.
11. Some reserve is gained by the large amount of coal stored on the grate in the event of coal handling plant failure.

Disadvantages :

1. Construction is complicated.
2. In case of very large units the initial cost may be rather higher than with pulverised fuel.
3. There is always a certain amount of loss of coal in the form of riddling through the grates.
4. Sudden variations in the steam demand cannot be met to the same degree.
5. Troubles due to slagging and clinkering of combustion chamber walls are experienced.
6. Banking and standby losses are always present.
7. Structural arrangements are not so simple and surrounding floors have to be designed for heavy loadings.
8. There is excessive wear of moving parts due to abrasive action of coal.

Classification of stoker firing :

Automatic stokers are *classified* as follows :

1. Overfeed stokers.
2. Underfeed stokers.

In case of overfeed stokers, the coal is fed into the grate *above* the point of air admission and in case of underfeed stokers, the coal is admitted into the furnace *below* the point of air admission.

1. Overfeed stokers :

Principle of operation. Refer to Fig. 2.11. The principle of an overfeed stoker is discussed below :

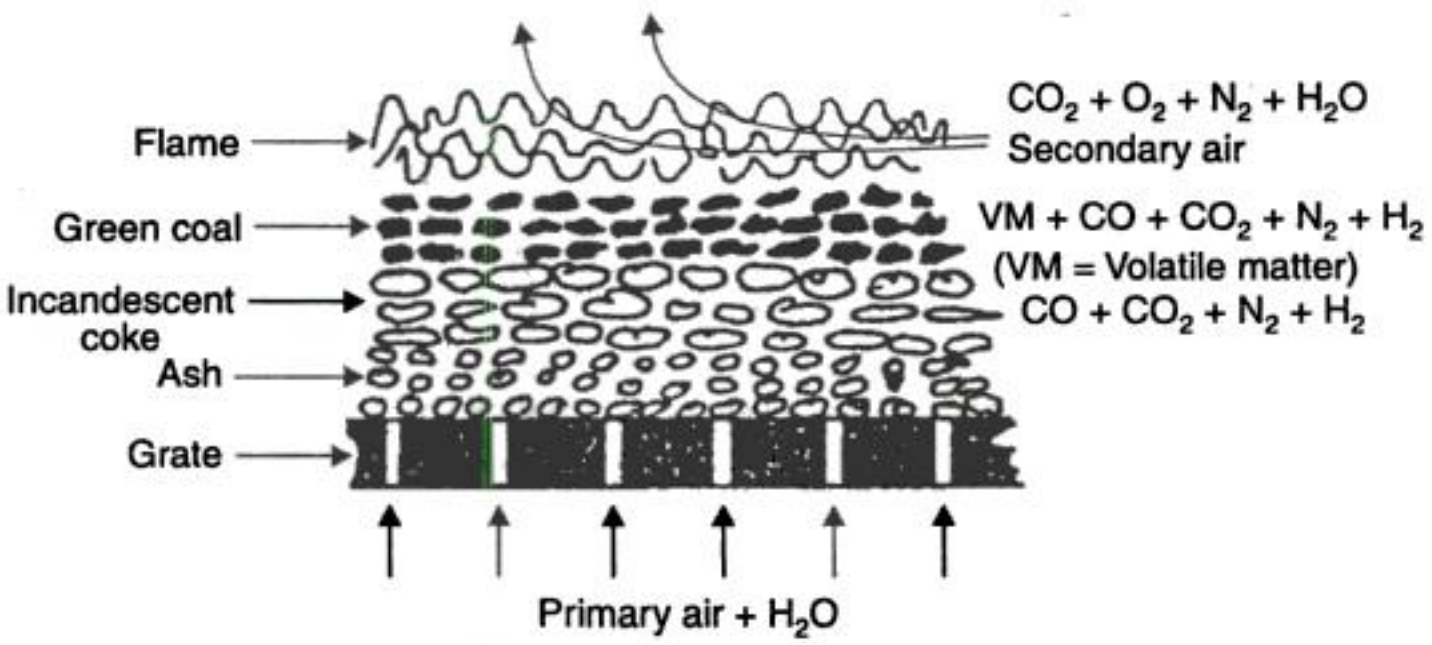

Fig. 2.11. Principle of overfeed stoker.

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The fuel bed section receives fresh coal on top surface. The ignition plane lies between green coal and incandescent coke.

The air (with its water vapour content from atmosphere) enters the bottom of the grate under pressure. In flowing through the grate opening the air is heated while it cools the grate. The warm air then passes through a layer of hot ashes and picks up the heat energy.

The region immediately above the ashes contains a mixture of incandescent coke and ash, coke content increasing in upward direction. As the air comes in contact with incandescent coke, the oxygen reacts with carbon to form carbondioxide. Water vapour entering with the air reacts with coke to form CO_2, CO and free H_2. Upon further travel through the incandescent region some of the CO_2 reacts with coke to form CO. Hence no free O_2 will be present in the gases leaving the incandescent region.

Fresh fuel undergoing distillation of its volatile matter forms the top-most layer of the fuel bed. Heat for distillation and eventually ignition comes from the following *four sources* :

(*i*) By conduction from the incandescent coke below.

(*ii*) From high temperature gases diffusing through the surface of the bed.

(*iii*) By radiation from flames and hot gases in the furnace.

(*iv*) From the hot furnace walls.

The ignition zone lies directly below the raw fuel undergoing distillation.

To burn the combustible gases, additional secondary air must be fed into the furnace to supply the needed oxygen. The secondary air must be injected at considerable speed to create turbulence and to penetrate to all parts of the area above the fuel bed. The combustible gases then completely burn in the furnace.

Fuel, coke and ash in the fuel bed move in direction opposite to that of air and gases. Raw fuel continually drops on the surface of the bed. The rising air feed cools the ash until it finally rests in a plane immediately adjacent to the grate.

Types of overfeed stokers

The "overfeed stokers" are used for large capacity boiler installation where the coal is burnt with pulverisation.

These stokers are mainly of following two types :

(*i*) Travelling grate stoker

(*a*) Chain grate type (*b*) Bar grate type

(*ii*) Spreader stoker.

(i) Travelling grate stoker :

These stokers may be *chain grate type or bar grate type*. These two differ only in the details of grate construction.

Fig. 2.12 shows a **"Chain grate stoker"**.

A chain grate stoker consists of flexible endless chain which forms a support for the fuel bed. The chain travels over two sprocket wheels one at the front and one at the rear of furnace. The front sprocket is connected to a variable speed drive mechanism. The speed of the stroker is 15 cm to 50 cm per minute.

The coal bed thickness is shown for all times by an index plate. This can be regulated either by adjusting the opening of fuel grate or by the speed control of the stoker driving motor.

The air is admitted from the underside of the grate which is divided into several compartments each connected to an air duct. The grate should be saved from being overheated. For this, coal should have sufficient ash content which will form a layer on the grate.

Since there is practically no agitation of the fuel bed, non-coking coals are best suited for chain grate stokers.

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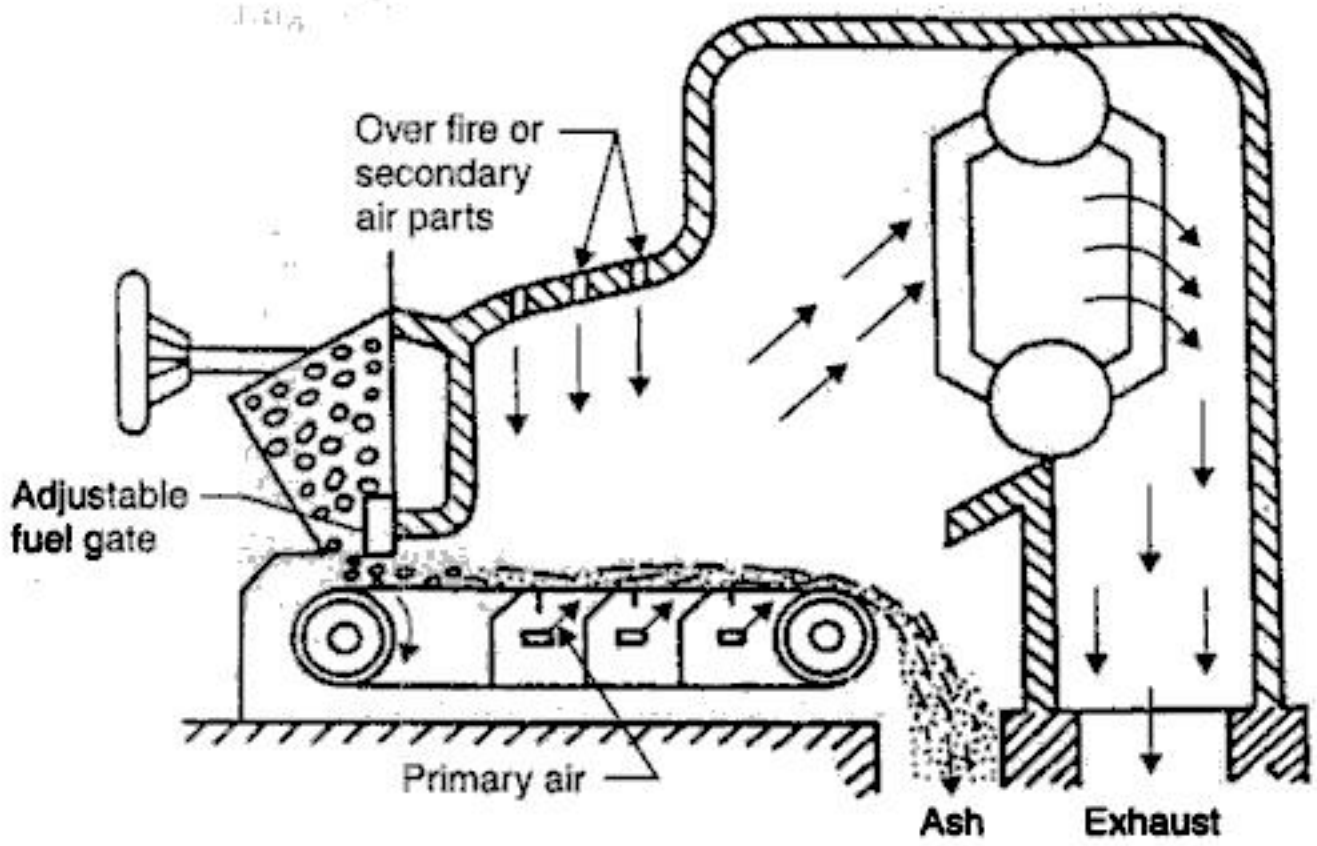

Fig. 2.12. Chain grate stoker.

The rate of burning with this stoker is 200 to 300 kg per m^2 per hour when forced draught is used.

Advantages of chain grate stoker :

1. Simple in construction.
2. Initial cost low.
3. Maintenance charges low.
4. Self-cleaning stoker.
5. Gives high release rates per unit volume of the furnace.
6. Heat release rates can be controlled just by controlling the speed of chain.

Disadvantages :

1. Preheated air temperatures are limited to 180°C maximum.
2. The clinker troubles are very common.
3. There is always some loss of coal in the form of fine particles through riddlings.
4. Ignition arches are required (to suit specific furnace conditions).
5. This cannot be used for high capacity boilers (200 tonnes/hr or more).

(ii) Spreader stoker. Refer to Fig. 2.13.

- In this type of stoker the coal is not fed into furnace by means of grate. The function of the grate is only to support a bed of ash and move it out of the furnace.
- From the coal hopper, coal is fed into the path of a rotor by means of a conveyer, and is thrown into the furnace by the rotor and is *burnt in suspension*. The *air for combustion* is supplied through the holes in the grate.
- The *secondary air* (or overfire *air*) to *create turbulence and supply oxygen for thorough combustion of coal* is supplied through *nozzles* located directly above the ignition arch.
- Unburnt coal and ash are deposited on the grate which can be moved periodically to remove ash out of the furnace.
- Spreader stokers *can burn any type of coal.*

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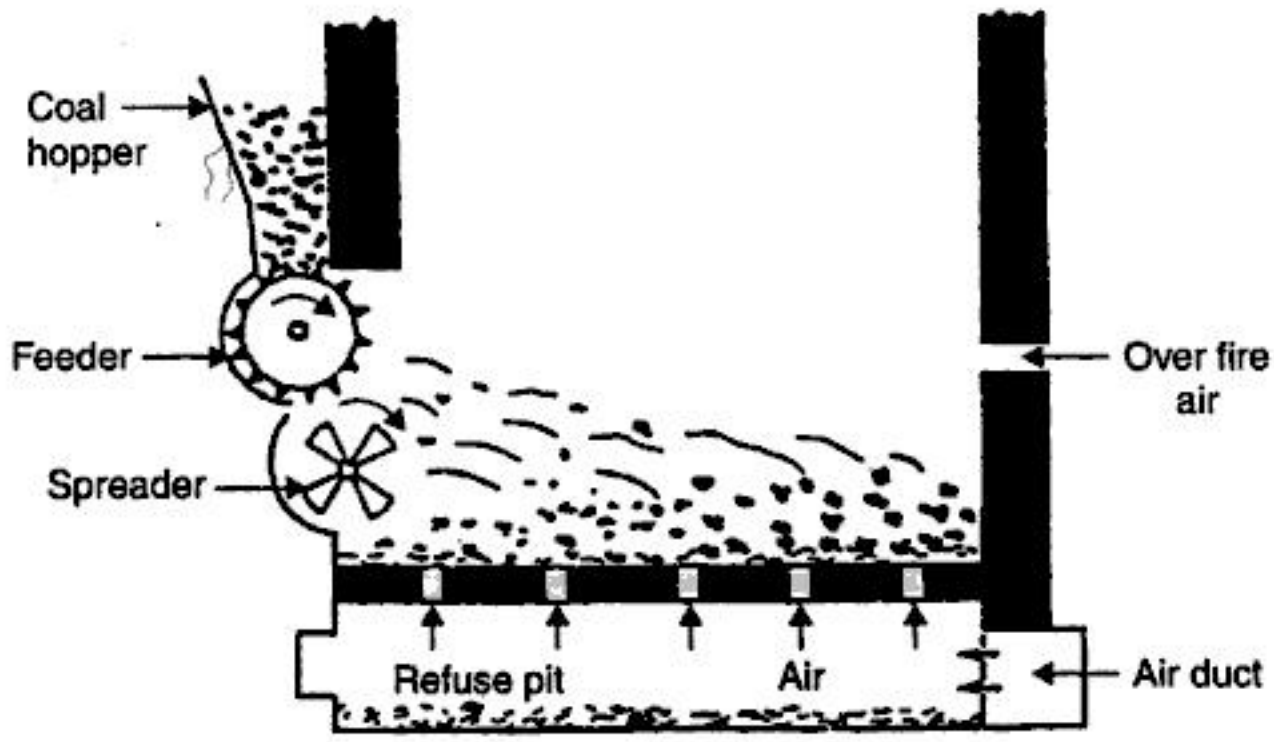

Fig. 2.13. Spreader stoker.

- This type of stoker can be used for boiler capacities from 70000 kg to 140000 kg of steam per hour. The heat release rate of 10×10^6 k cal/m^2-hr is possible with *stationary grate* and of 20×10^6 k cal/m^2-hr is possible with *travelling grate.*

Advantages :

1. A wide variety of coal can be burnt.
2. This stoker is simple to operate, easy to light up and bring into commission.
3. The use of high temperature preheated air is possible.
4. Operation cost is considerably low.
5. The clinking difficulties are reduced even with coals which have high clinkering tendencies.
6. Volatile matter is easily burnt.
7. Fire arches etc. are generally not required with this type of stokers.
8. As the depth of coal bed on the grate is usually limited to 10 to 15 cm only, fluctuating loads can be easily met with.

Disadvantages :

1. It is difficult to operate spreader with varying sizes of coal with varying moisture content.
2. Fly-ash is much more.
3. No remedy for clinker troubles.
4. There is a possibility of some fuel loss in the cinders up the stack because of the thin fuel bed and suspension burning.

2. Underfeed feeders :

Principle of operation. Refer to Fig. 2.14 (*a*).

- *The underfeed principle is suitable for burning the semi-bituminous and bituminous coals.*
- Air entering through the holes in the grate comes in contact with the raw coal (green coal). Then it passes through the incandescent coke where reactions similar to overfeed system take place. The gases produced then pass through a layer of ash. The secondary air is supplied to burn the combustible gases.

The underfeed stokers fall into two main groups, the *single retort* and *multi-retort stokers.*

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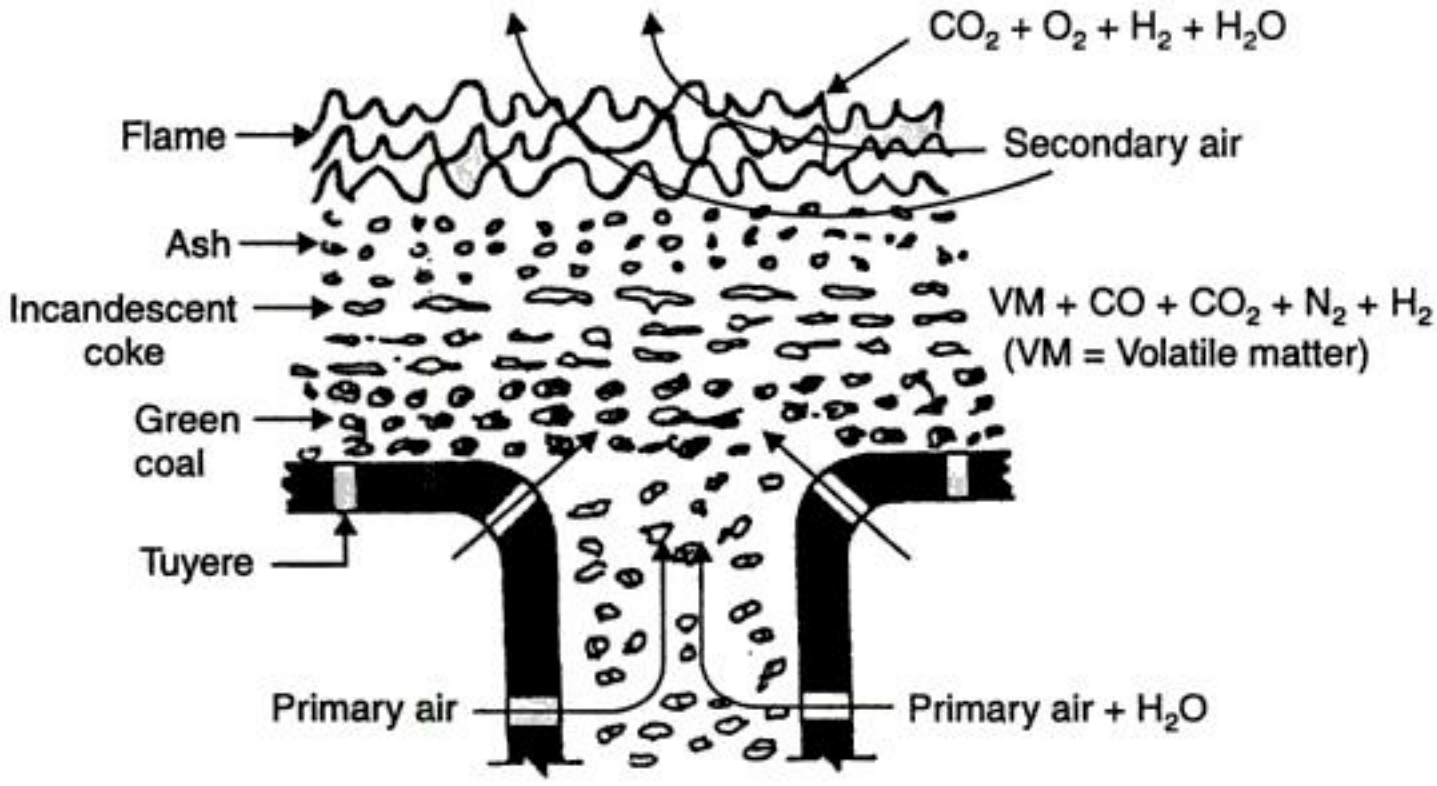

Fig. 2.14. (*a*) Principle of underfeed feeders.

Multi-retort underfeed stokers :

Refer to Fig. 2.14 (*b*).

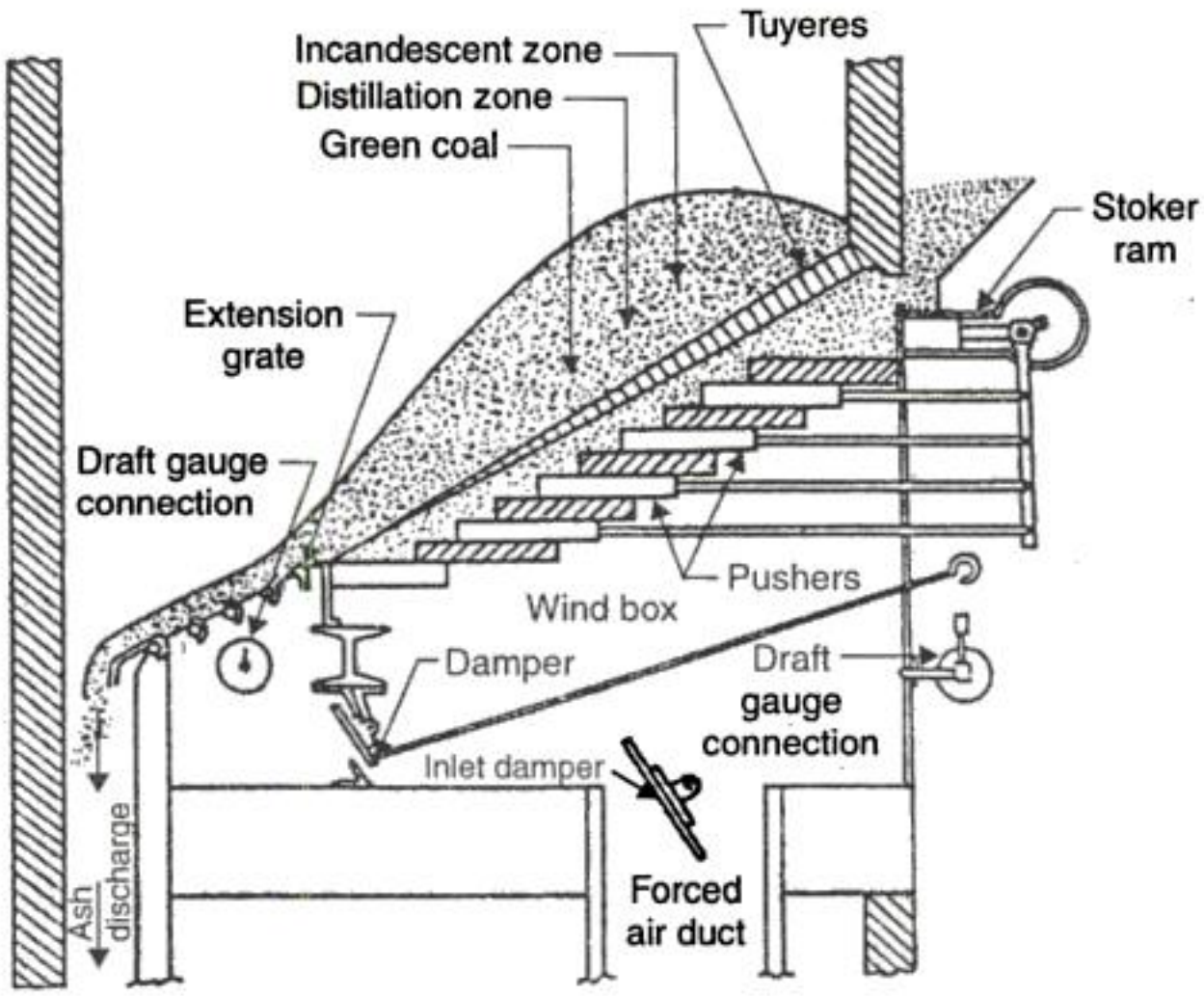

Fig. 2.14. (*b*) Multi-retort underfeed stokers.

- The stoker consists of a series of sloping parallel troughs formed by tuyere stacks. These troughs are called *retorts*. Under the coal hopper at the head end of the retorts, *feeding rams* reciprocate back and forth. With the ram in the outer position coal from the hopper falls into space vacated by the ram. On the inward stroke the ram forces the coal into the retort.

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- The height and profile of the fuel bed is controlled by *secondary*, or *distributing rams*. These rams oscillate parallel to the retort axes, the length of their stokes can be varied as needed. They slowly move the entire fuel bed down the length of the stoker.
- At the rear of the stoker the partly burned fuel bed moves onto an *extension grate* arranged in sections. These sections also oscillate parallel to the fuel-bed movement. The sharp slope of the stoker aids in moving the fuel bed. Fuel-bed movement keeps it slightly agitated to break up clinker formation. From extension grate the ash moves onto ash dump plate. Tilting the dump plate at long intervals deposits the ash in the ashpit below.
- *Primary air* from the wind box underneath the stoker enters the fuel bed through holes in the vertical sides of the tuyeres. The extension grate carries a much thinner fuel bed and so must have a lower air pressure under it. The air entering from the main wind box into the extension-grate wind box is regulated by a *controlling air damper*.

In this stoker the number of retorts may vary from 2 to 20 with coal burning capacity ranging from 300 kg to 2000 kg per hour per retort.

Underfeed stokers are *suitable for non-clinkering, high voltatile coals having caking properties and low ash contents*.

Advantages :

1. High thermal efficiency (as compared to chain grate stokers).
2. Combustion rate is considerably higher.
3. The grate is self cleaning.
4. Part load efficiency is high particularly with multi-retort type.
5. Different varieties of coals can be used.
6. Much higher steaming rates are possible with this type of stoker.
7. Grate bars, tuyeres and retorts are not subjected to high temperature as they remain always in contact with fresh coal.
8. Overload capacity of the boiler is high as large amount of coal is carried on the grate.
9. Smokeless operation is possible even at very light load.
10. With the use of clinker grinder, more heat can be liberated out of fuel.
11. Substantial amount of coal always remains on the grate so that the boiler may remain in service in the event of temporary breakdown of the coal supply system.
12. It can be used with all refractory furnaces because of non-exposure of stoker mechanism to the furnace.

Disadvantages :

1. High initial cost.
2. Require large building space.
3. The clinker troubles are usually present.
4. Low grade fuels with high ash content cannot be burnt economically.

2.9.3.2. Pulverised fuel firing

In pulverised fuel firing system the *coal is reduced to a fine powder with the help of grinding mill and then projected into the combustion chamber with the help of hot air current*. The amount of air required (known as *secondary air*) to complete the combustion is supplied separately to the combustion chamber. The resulting turbulence in the combustion chamber helps for uniform mixing of fuel and air and thorough combustion. *The amount of air which is used to carry the coal and to dry*

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it before entering into the combustion chamber is known as **Primary air** *and the amount of air which is supplied separately for completing the combustion is known as* **Secondary air.**

The *efficiency* of the pulverised fuel firing system mostly *depends upon the size of the powder*. The fineness of the coal should be such as 70% of it would pass through a 200 mesh sieve and 90% through 50 mesh sieve.

Fig. 2.15 shows elements of pulverised coal system.

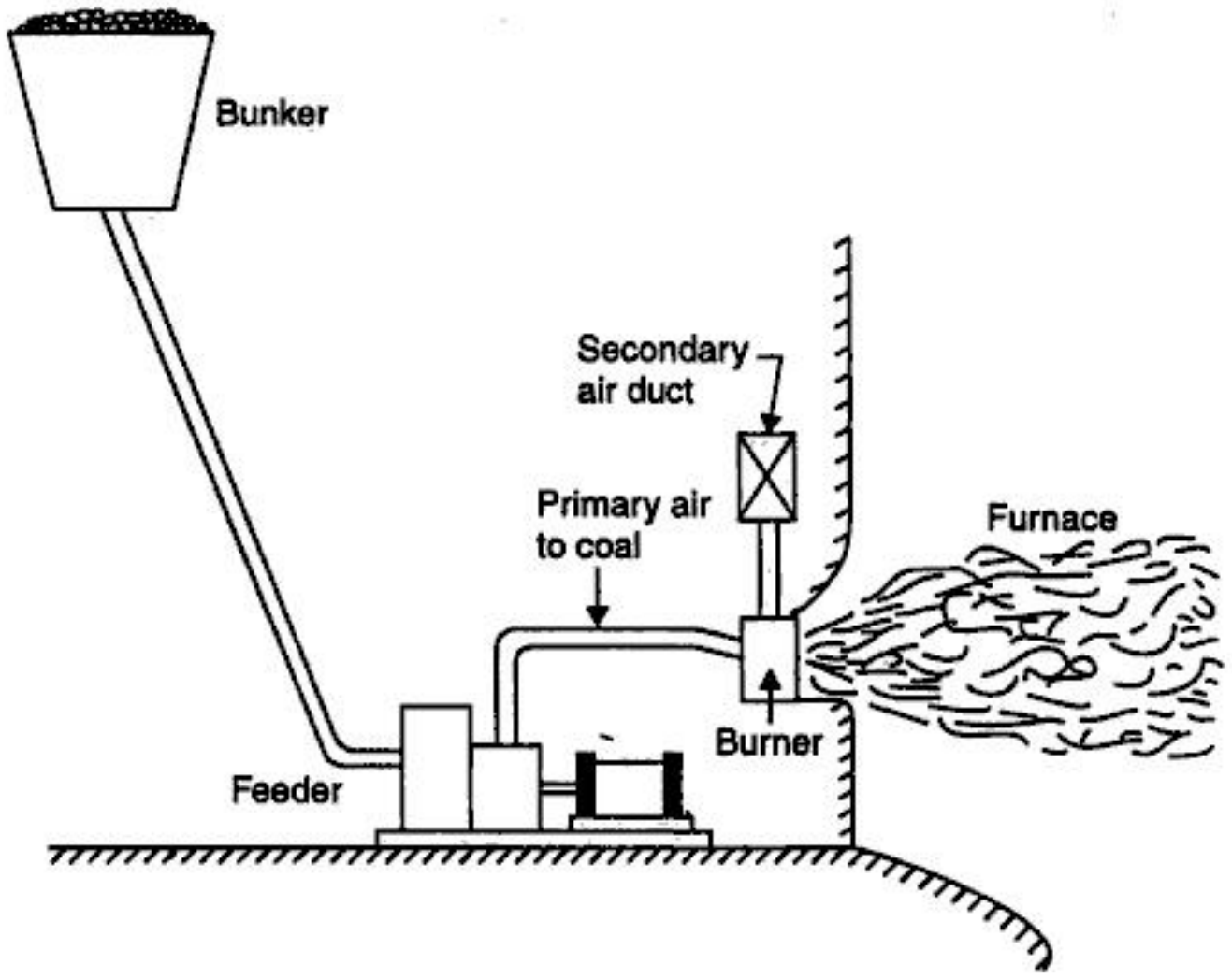

Fig. 2.15. Elements of pulverised coal system.

Advantages :

1. Any grade of coal can be used since coal is powdered before use.
2. The rate of feed of the fuel can be regulated properly resulting in fuel economy.
3. Since there is almost complete combustion of the fuel there is increased rate of evaporation and higher boiler efficiency.
4. Greater capacity to meet peak loads.
5. The system is practically free from sagging and clinkering troubles.
6. No standby losses due to banked fires.
7. Practically no ash handling problems.
8. No moving part in the furnace is subjected to high temperatures.
9. This system works successfully with or in combination with gas and oil.
10. Much smaller quantity of air is required as compared to that of stoker firing.
11. Practically free from clinker troubles.
12. The external heating surfaces are free from corrosion.
13. It is possible to use highly preheated secondary air (350°C) which helps for rapid flame propagation.
14. The furnace volume required is considerably less.

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Disadvantages :

1. High capital cost.
2. Lot of fly-ash in the exhaust, which makes the removing of fine dust uneconomical.
3. The possibility of explosion is more as coal burns like gas.
4. The maintenance of furnace brickwork is costly.
5. Special equipment is needed to start this system.
6. The skilled operators are required.
7. A separate coal preparation plant is necessary.
8. High furnace temperatures cause rapid deterioration of the refractory surfaces of the furnace.
9. Nuisance is created by the emission of very fine particles of grit and dust.
10. Fine regular grinding of fuel and proper distribution to burners is usually difficult to achieve.

Pulverised Fuel Handling

Basically, pulverised fuel plants may be divided into the following *two systems* :

1. Unit system.
2. Central system.

Unit system :

A unit system is shown in Fig. 2.16.

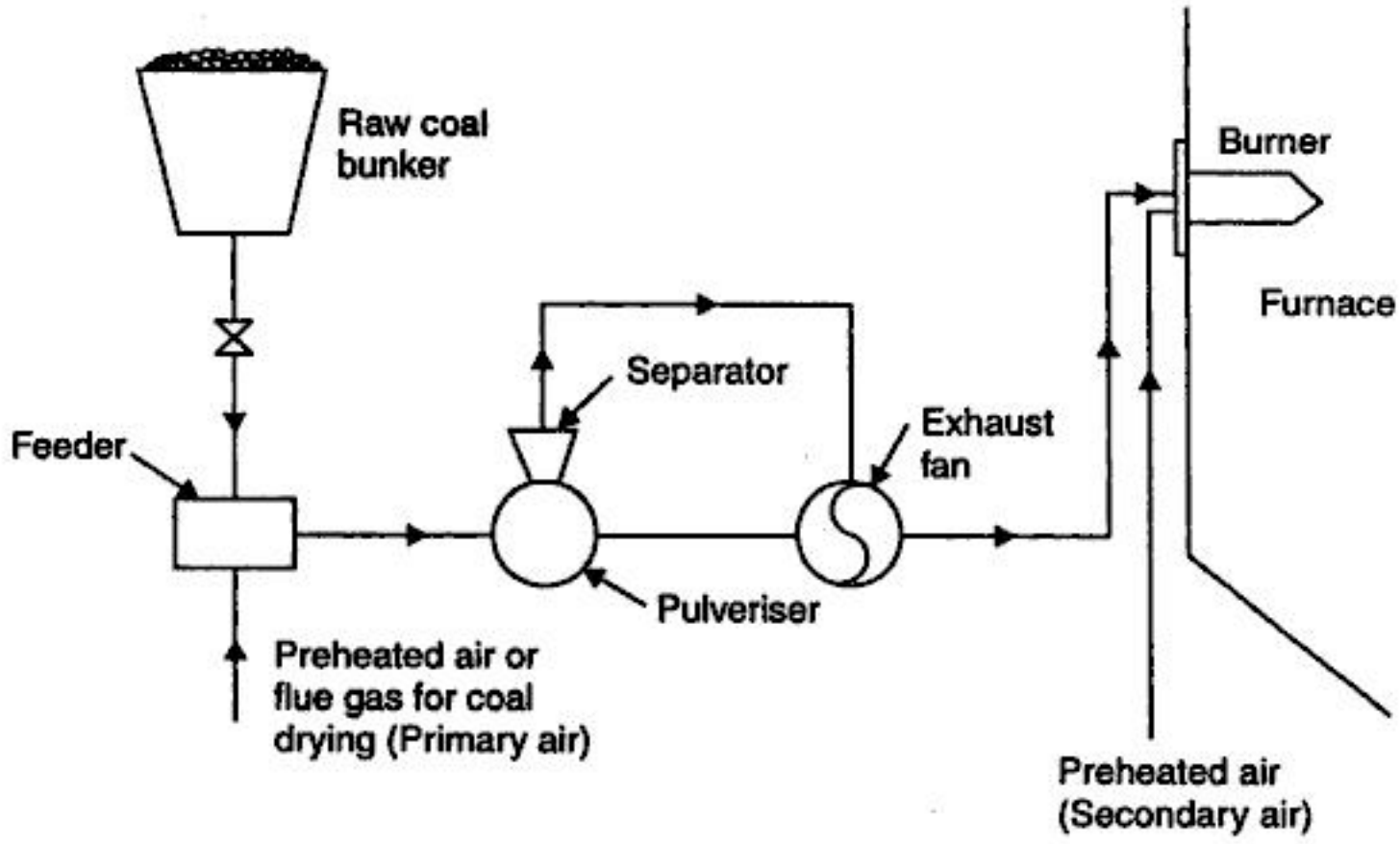

Fig. 2.16. Unit system.

Most pulverised coal plants are now being installed with unit pulveriser.

The *unit system* is so called from the fact that each burner or burner group and the pulveriser constitute a unit. Crushed coal is fed to the pulverising mill at a variable rate governed by the combustion requirements of the boiler and furnace. Primary air is admitted to the mill and becomes the transport air which carries the coal through the short delivery pipe to the burner. This air may be preheated if mill drying is desirable.

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Advantages :

1. The layout is simple and permits easy operation.
2. It is cheaper than central system.
3. Less spaces are required.
4. It allows direct control of combustion from the pulveriser.
5. Maintenance charges are less.
6. There is no complex transportation system.
7. In a replacement of stokers, the old conveyor and bunker equipment may be used.
8. Coal which would require drying in order to function satisfactorily in the central system may usually be employed without drying in the unit system.

Disadvantages :

1. Firing aisle is obstructed with pulverising equipment, unless the latter is relegated to a basement.
2. The mills operate at variable load, a condition not especially conducive to best results.
3. With load factors in common practice, total mill capacity must be higher than for the central system.
4. Flexibility is less than central system.

Central system :

This system is illustrated in Fig. 2.17.

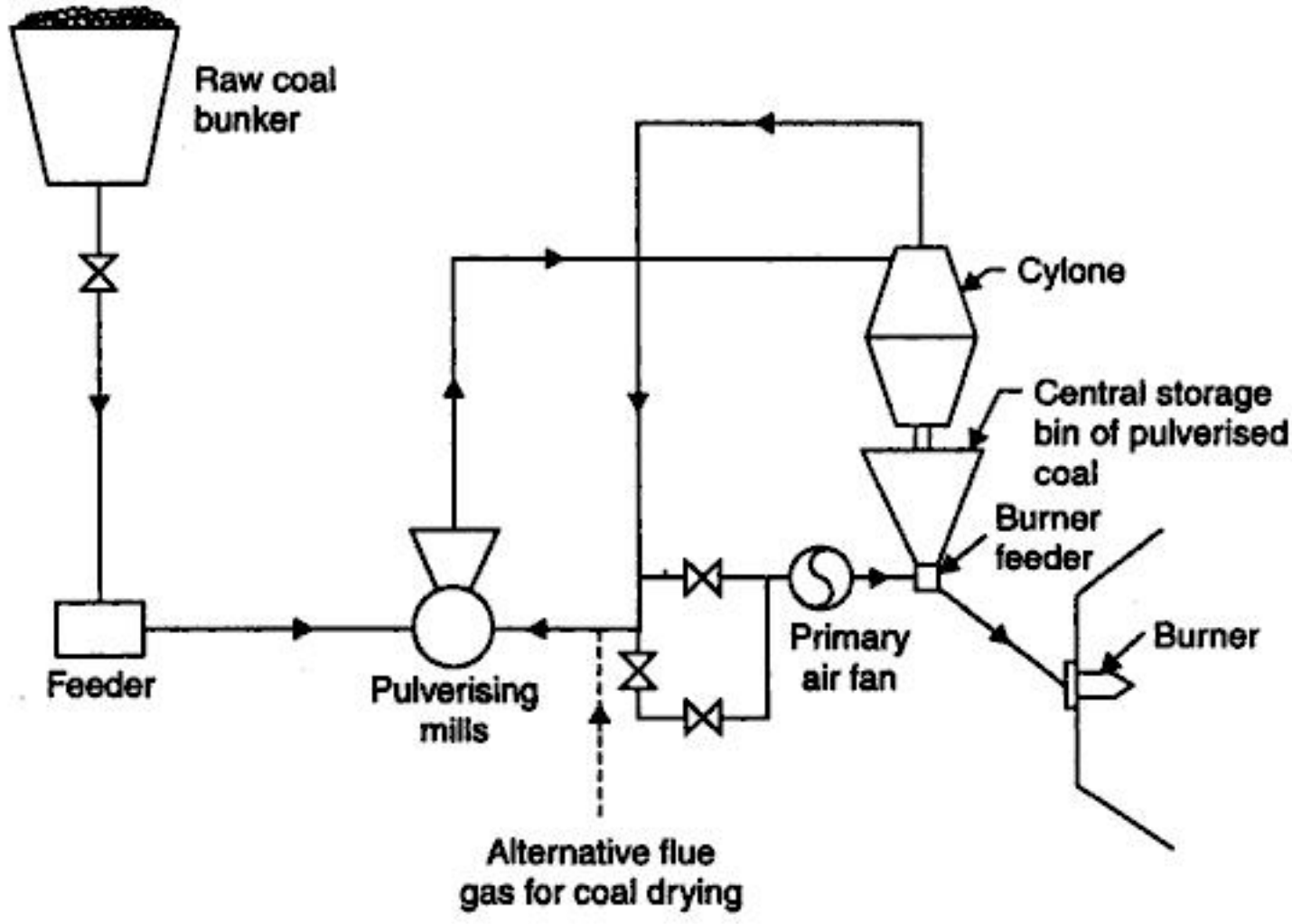

Fig. 2.17. Central system.

A central pulverising system employs a limited number of large capacity pulverisers at a central point to prepare coal for all the burners. Driers, if required, are conveniently installed at this point. From the pulverisers the coal is transported to a central storage bin where it is deposited and its transporting air vented from the bin through a "*cyclone*". This bin may contain from 12 to 24

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hours supply of pulverised coal. From the bin the coal is metered to the burners by motor-driven feeders of varied design. Primary air, added at the feeders, floats the coal to the burners.

Advantages :

1. Offers good control of coal fineness.
2. The pulverising mill may work at constant load because of the storage capacity between it and the burners.
3. The boiler aisels are unobstructed.
4. More latitude in the arrangement and number of burners is allowed to the designers.
5. The large storage is protection against interruption of fuel supply to the burners.
6. Less labour is required.
7. Power consumption per tonne of coal handled is low.
8. Burners can be operated independent of the operation of coal preparation plant.
9. Fans handle only air, as such, there is no problem of excessive wear as in case of unit system, where air and coal both are handled by the fan.

Disadvantages :

1. Driers are usually necessary.
2. Fire hazard of quantities of stored pulverised coal.
3. Central preparation may require a separate building.
4. Additional cost and complexity of coal transportation system.
5. Power consumption of auxiliaries is high.

Pulveriser. Coal is pulverised in order to increase its surface exposure, thus promoting rapid combustion without using large quantities of excess air. A pulveriser is the most important part of a pulverised coal system. Pulverisers (sometimes called *mills*) are classified as follows :

1. Attrition mills :
   (*i*) Bowl mills
   (*ii*) Ball and race mills.
2. Impact mills :
   (*i*) Ball mills
   (*ii*) Hammer mills.

Pulverisers are driven by electric motors with the feeders either actuated by the main drive or by a small d.c. motor, depending upon the control used.

2.9.4. Burners

Primary air that carries the powdered coal from the mill to the furnace is only about 20% of the total air needed for combustion. Before the coal enters the furnace, it must be mixed with additional air, known as *secondary air,* in burners mounted in the furnace wall. *In addition to the prime function of mixing, burners must also maintain stable ignition of fuel-air mix* and *control the flame shape and travel in the furnace.* Ignition depends on the rate of flame propagation. To prevent flash back into the burner, the coal-air mixture must move away from the burner at a rate equal to flame-front travel. *Too much secondary air can cool the mixture and prevent its heating to ignition temperature.*

The *requirements of a burner* can be summarised as follows :

(*i*) The coal and air should be so handled that there is stability of ignition.

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(*ii*) The combustion is complete.

(*iii*) In the flame the heat is uniformly developed avoiding any superheat spots.

(*iv*) Adequate protection against overheating, internal fires and excessive abrasive wear.

2.9.4.1. Pulverised fuel burners

Pulverised fuel burners may be *classified* as follows :

1. Long flame burners.
2. Turbulent burners.
3. Tangential burners.
4. Cyclone burners.

2.9.4.2. Oil burners

Principle of oil firing. *The functions of an oil burner are to mix the fuel and air in proper proportion and to prepare the fuel for combustion.* Fig. 2.18 shows the principle of oil firing.

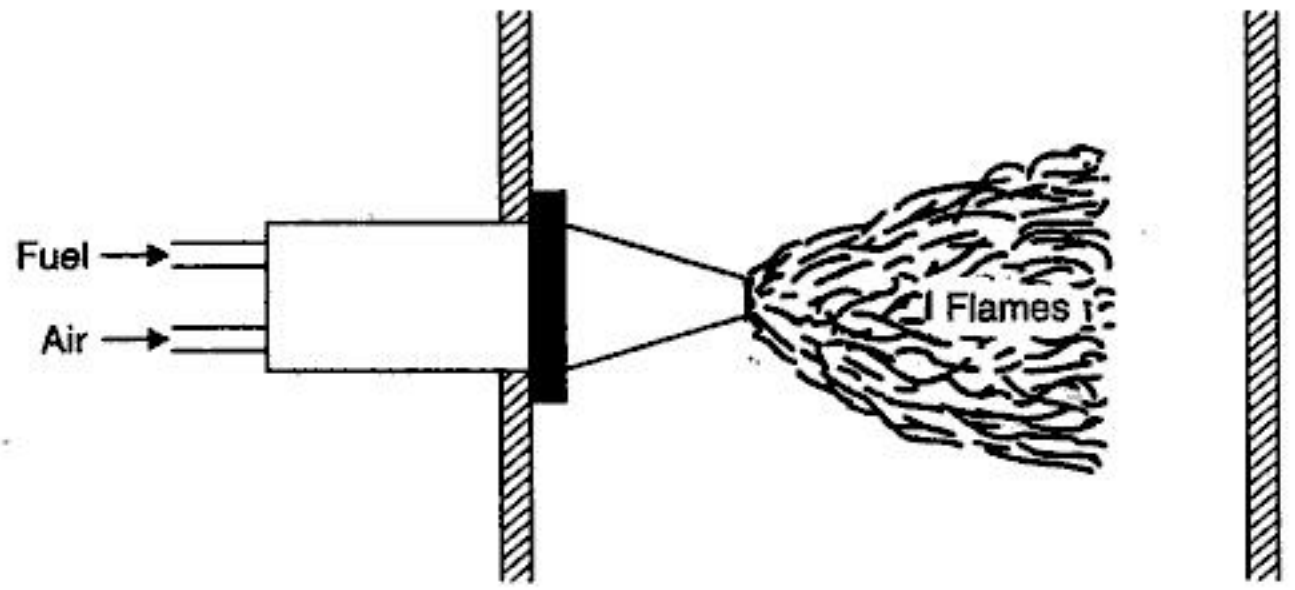

Fig. 2.18. Principle of oil firing.

Classification of oil burners. The oil burners may be *classified* as :

1. *Vapourising oil burners :*
   - (*a*) Atmospheric pressure atomising burner
   - (*b*) Rotating cup burner
   - (*c*) Recirculation burner
   - (*d*) Wick type burner.
2. *Atomising fuel burners :*
   - (*a*) Mechanical or oil pressure atomising burner
   - (*b*) Steam or high pressure air atomising burner
   - (*c*) Low pressure air atomising burner.

2.9.4.3. Gas burners

Gas burning claims the following *advantages* :

(*i*) It is much simpler as the fuel is ready for combustion and requires no preparation.

(*ii*) Furnace temperature can be easily controlled.

(*iii*) A long slow burning flame with uniform and gradual heat liberation can be produced.

(*iv*) Cleanliness.

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(*v*) High chimney is not required.

(*vi*) No ash removal is required.

For generation of steam, natural gas is invariably used in the following cases :

(*i*) Gas producing areas.

(*ii*) Areas served by gas transmission lines.

(*iii*) Where coal is costlier.

Typical gas burners used are shown in Fig. 2.19 to 2.20.

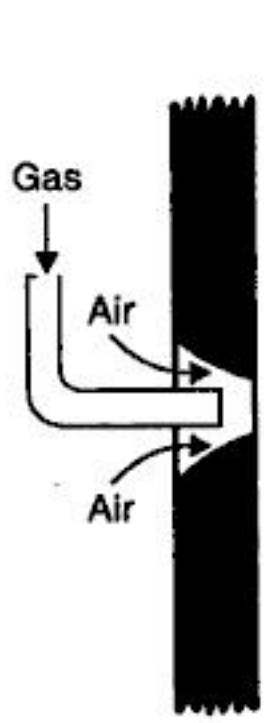

Fig. 2.19

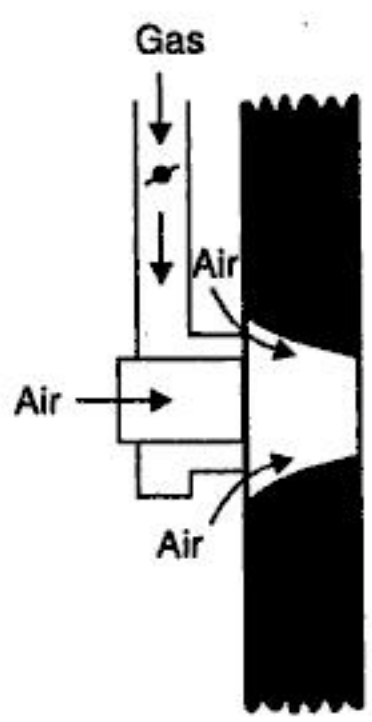

Fig. 2.20

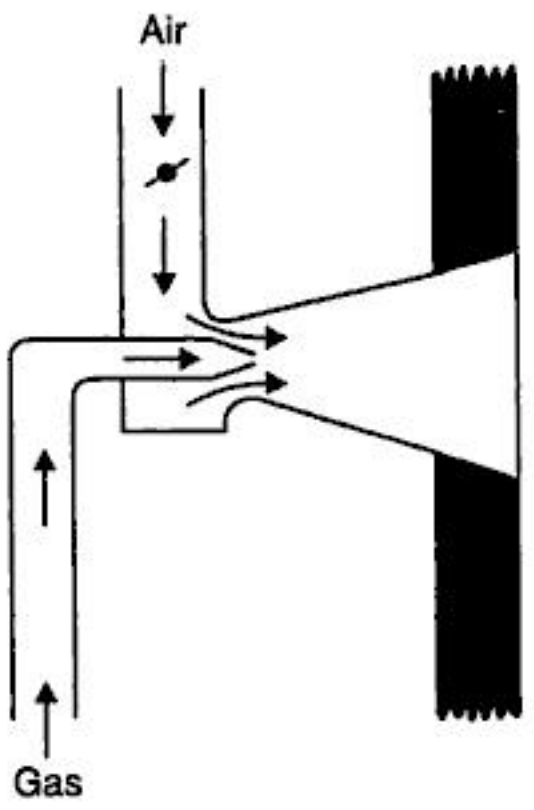

Fig. 2.21

Refer to Fig. 2.19. In this burner the mixing is poor and a fairly long flame results.

Refer to Fig. 2.20. This is a *ring type burner* in which a short flame is obtained.

Refer to Fig. 2.21. This arrangement is used when both gas and air are under pressure.

In order to prevent the flame from turning back the velocity of the gas should be more than the "*rate of flame propagation*".

2.10. FLUIDISED BED COMBUSTION (FBC)

*A **fluidised bed** may be defined as the bed of solid particles behaving as a fluid.* The *principle of FBC-system* is given below :

When a gas is passed through a packed bed of finely divided solid particles, it experiences a pressure drop across the bed. At low gas velocities, this pressure drop is small and does not disturb the particles. But if the gas velocity is increased further, a stage is reached, *when particles are suspended in the gas stream and the packed bed becomes a 'fluidised bed'*. With further increase in gas velocity, the bed becomes turbulent and rapid mixing of particles occurs. In general, the behavior of this mixture of solid particles and gas is like a fluid. Burning of a fuel in such a state is known as a *fluidised bed combustion*.

Fig. 2.22 shows the arrangement of the FBC system.

On the distributor plate are fed the fuel and inert material *dolomite* and from its bottom air is supplied. The high velocity of air keeps the solid feed material in suspending condition during burning. The generated heat is rapidly transferred to the water passing through the tubes immersed

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in the bed and generated steam is taken out. During the burning sulphur dioxide formed is absorbed by the dolomite and prevents its escape with the exhaust gases. The molten slag is tapped from the top surface of the bed.

The primary object of using the *inert material* is to control the bed temperature, it accounts for 90% of the bed volume. It is very necessary that the selection of an inert material should be done judiciously as it remains with the fuel in continuous motion and at high temperature to the tune of 800°C. Moreover, the inert material should not disintegrate coal, the parent material of the bed.

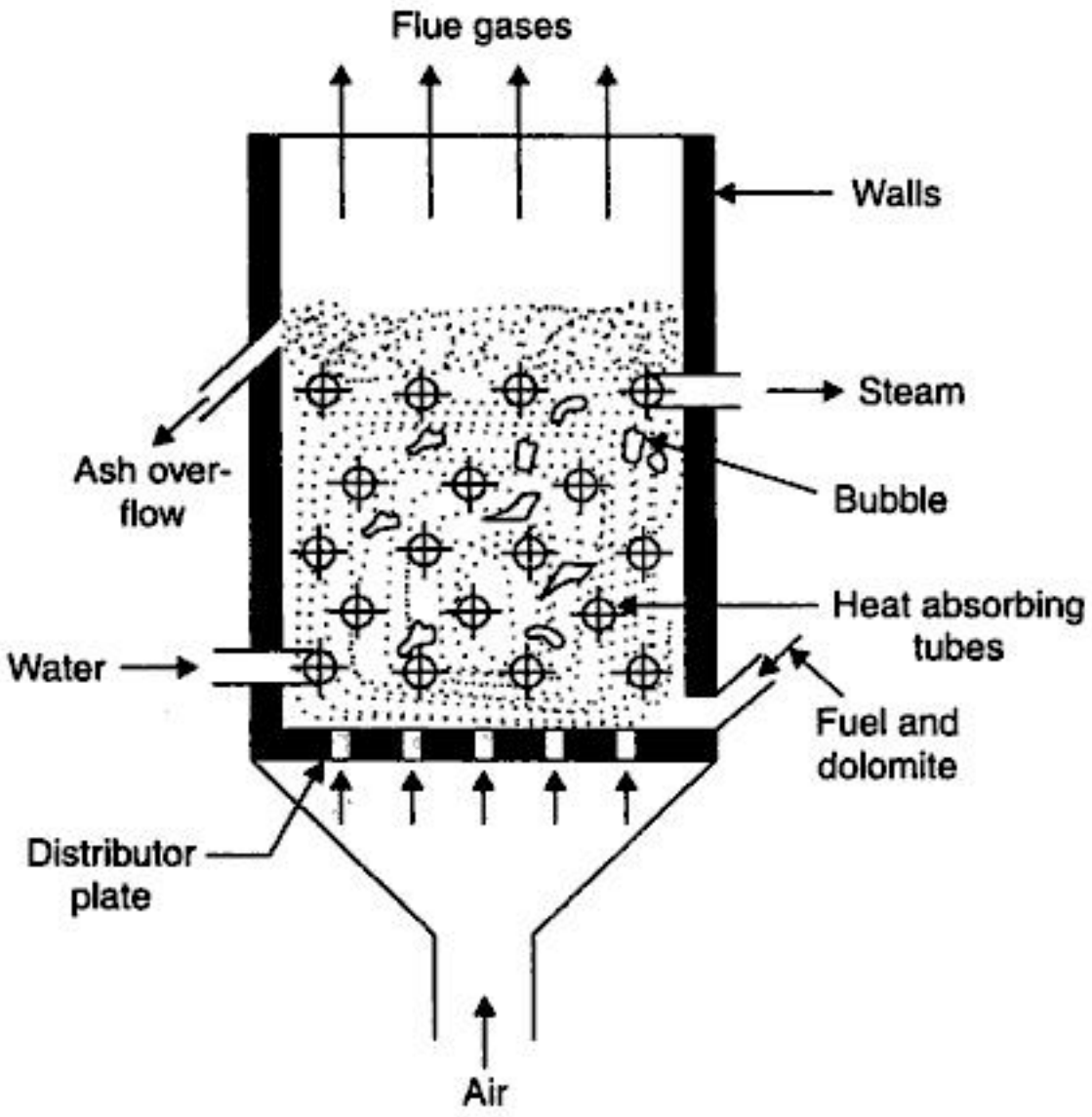

Fig. 2.22. Basic FBC system.

The cost economic shows that a saving of about 10% in operating cost and 15% capital cost could be achieved for a unit rating of 120 MW and it may be still higher for bigger units.

Advantages :

1. As a result of better heat transfer, the unit size and hence the *capital costs are reduced.*
2. It can respond rapidly to changes in load demand (since thermal equilibrium between air and coal particles in the bed is quickly established).
3. Low combustion temperatures (800 to 950°C) inhibits the formation of nitrogen oxides like nitric oxide and nitrogen dioxide.
4. Since combustion temperatures are low the fouling and corrosion of tubes is reduced considerably.
5. As it is not necessary to grind the coal very fine as is done in pulverised fuel firing, therefore, the cost of coal crushing is reduced.
6. Pollution is controlled and combustion of high-sulphur coal is possible.

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7. FBC system can use solid, liquid or gaseous fuel or mix as well as domestic and industrial waste. Any variety of coal can be used successfully.
8. Combustion temperature can be controlled accurately.
9. The system can be readily designed for operation at raised combustion pressure, owing to the simplicity of arrangement, small size of the plant and reduced likelihood of corrosion or erosion of gas turbine blades.
10. The combustion in conventional system becomes unstable when the ash exceeds 48% but even 70% ash containing coal can be efficiently burned in FBC.
11. The large quantity of bed material acts as a thermal storage which reduces the effect of any fluctuation in fuel feed ratio.

2.11. ASH HANDLING

A huge quantity of ash is produced in central stations, sometimes being as much as 10 to 20% of the total quantity of coal burnt in a day. Hundreds of tonnes of ash may have to be handled every day in large power stations and mechanical devices become indispensable. A station using low grade fuel has to deal with large quantities of ash.

Handling of ash includes :

(*i*) Its removal from the furnace.

(*ii*) Loading on the conveyers and delivery to the fill or dump from where it can be disposed off by sale or otherwise.

Handling of ash is a problem because ash coming out of the furnace is too hot, it is dusty and irritating to handle and is accompanied by some poisonous gas. Ash needs to be *quenched* before handling due to following *reasons* :

(*i*) Quenching reduces corrosion action of the ash.

(*ii*) It reduces the dust accompanying the ash.

(*iii*) It reduces temperature of the ash.

(*iv*) Ash forms clinkers by fusing in large lumps and by quenching clinkers will disintegrate.

2.11.1. Ash Handling Equipment

A *good ash handling plant* should have the following *characteristics* :

1. It should have enough capacity to cope with the volume of ash that may be produced in a station.
2. It should be able to handle large clinkers, boiler refuse, soot etc., with little personal attention of the workmen.
3. It should be able to handle hot and wet ash effectively and with good speed.
4. It should be possible to minimise the corrosive or abrasive action of ashes and dust nuisance should not exist.
5. The plant should not cost much.
6. The operation charges should be minimum possible.
7. The operation of the plant should be noiseless as much as possible.
8. The plant should be able to operate effectively under all variable load conditions.
9. In case of addition of units, it should need minimum changes in original layout of plant.
10. The plant should have high rate of handling.

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The *commonly used equipment for ash handling* in large and medium size plants may comprise of :

(*i*) Bucket elevator
(*ii*) Bucket conveyor
(*iii*) Belt conveyor
(*iv*) Pneumatic conveyor
(*v*) Hydraulic sluicing equipment
(*vi*) Trollies or rail cars etc.

Fig. 2.23 shows the outline of ash disposal equipment.

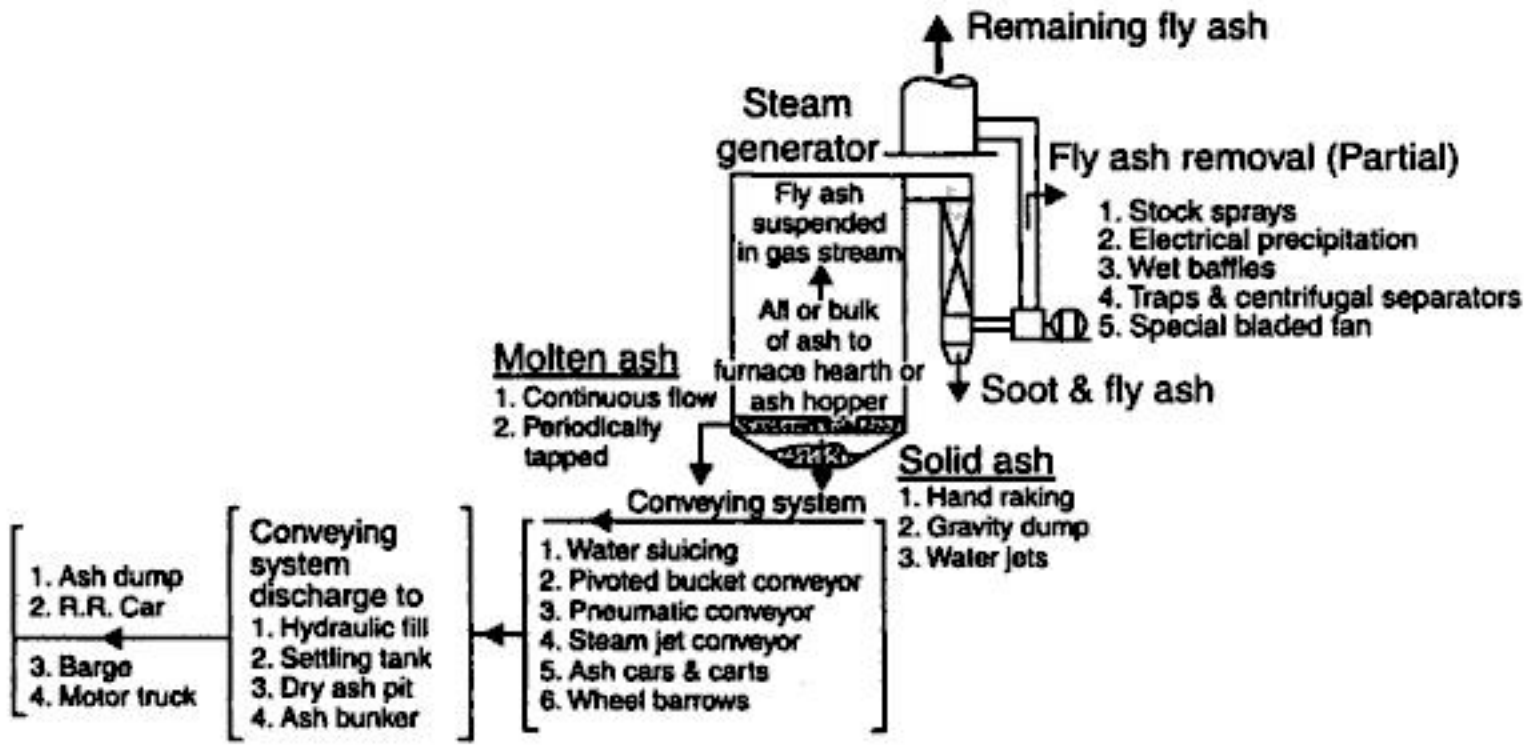

Fig. 2.23. Outline of ash disposal equipment.

2.11.2. Ash Handling Systems

The modern ash-handling systems are mainly *classified* into *four* groups :

1. Mechanical handling system
2. Hydraulic system
3. Pneumatic system
4. Steam jet system.

2.12. DUST COLLECTION

2.12.1. Introduction

The products of combustion of coal-fed fires contain particles of solid matter floating in suspension. This may be smoke or dust. If *smoke*, the indication is that combustion conditions are faulty, and the proper remedy is in the design and management of the furnace. If *dust*, the particles are mainly fine ash particles called "*Fly-ash*" intermixed with some quantity of carbon-ash material called "*cinder*". *Pulverised coal and spreader stoker firing units are the principle types causing difficulty from this source.* Other stokers may produce minor quantities of dust but generally not enough to demand special gas cleaning equipment. The two mentioned are troublesome because coal is burned in suspension—in a turbulent furnace atmosphere and every opportunity is offered for the gas to pick up the smaller particles and sweep them along with it.

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The size of the dust particles is measured in *microns*. The micron is one millionth of a metre. As an indication of the scale of this measure, the diameter of a human hair is approximately 80 microns. Typical classification of particles by name is given in Fig. 2.24, but the limits shown are, for the most part, arbitrary. A critical characteristic of dust is its "*Settling Velocity*" in still air. *This is proportional to the product of the square of micron size and mass density*.

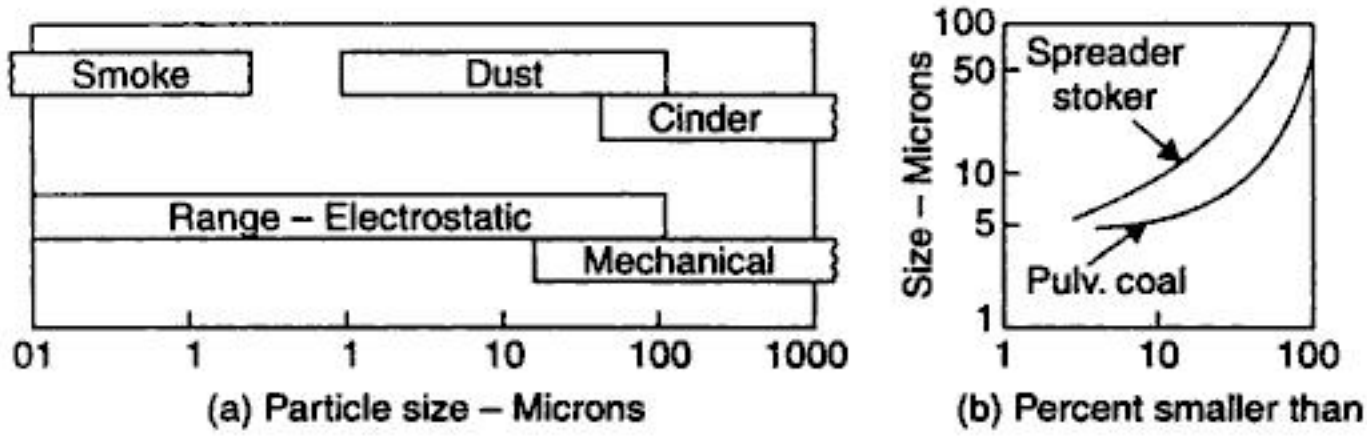

Fig. 2.24. Typical particle sizes : (*a*) Flue gas particles and ranges of collecting equipment. (*b*) Typical distribution of particle size in products of combustion.

2.12.2. Removal of Smoke

Smoke is produced due to the incomplete combustion of fuels. Smoke particles are less than 1 micron in size. The smoke disposal to the atmosphere is not desirable due to the following *reasons* :

(*i*) Smoke is produced due to incomplete combustion of coal. This will create a big economic loss due loss of heating value of coal.

(*ii*) A smoky atmosphere is unhealthy.

(*iii*) Smoke corrodes the metals, darkens the paints and gives lower standards of cleanliness.

In order to check the nuisance of smoke the coal should be completely burnt in the furnace. *The presence of dense smoke indicates poor furnace conditions and a loss in efficiency and capacity of a boiler plant.*

2.12.3. Removal of Dust and Dust Collectors

The removal of dust and cinders from flue gas can usually be effected to the required degree by commercial dust collectors.

The dust collectors may be *classified* as follows :

1. Mechanical dust collectors :

(*i*) Wet type (Scrubbers)

(*a*) Spray type

(*b*) Packed type

(*c*) Impingement type

(*ii*) Dry type

(*a*) Gravitational separators

(*b*) Cyclone separators

2. Electrical dust collectors :

(*i*) Rod type

(*ii*) Plate type.

2.12.4. Uses of Ash and Dust

The *uses of ash and dust* are listed below :

1. Ash is widely used in the production of cement.

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2. Ash is used in the production of concrete. 20 percent fly-ash and 30 percent bottom ash are presently used constructively in U.S.A.

3. Because of their better alkali values, they are used for treating acidic soils. It has been found that if ash is used in limited quantity in soil, it increases the yield of corn, turnip etc.

4. From the ash, the metals such as Al, Fe, Si and titanium can be recovered.

2.12.5. General Layout of Ash Handling and Dust Collection System

Fig. 2.25 shows the general layout of ash handling and dust collection system which is self explanatory.

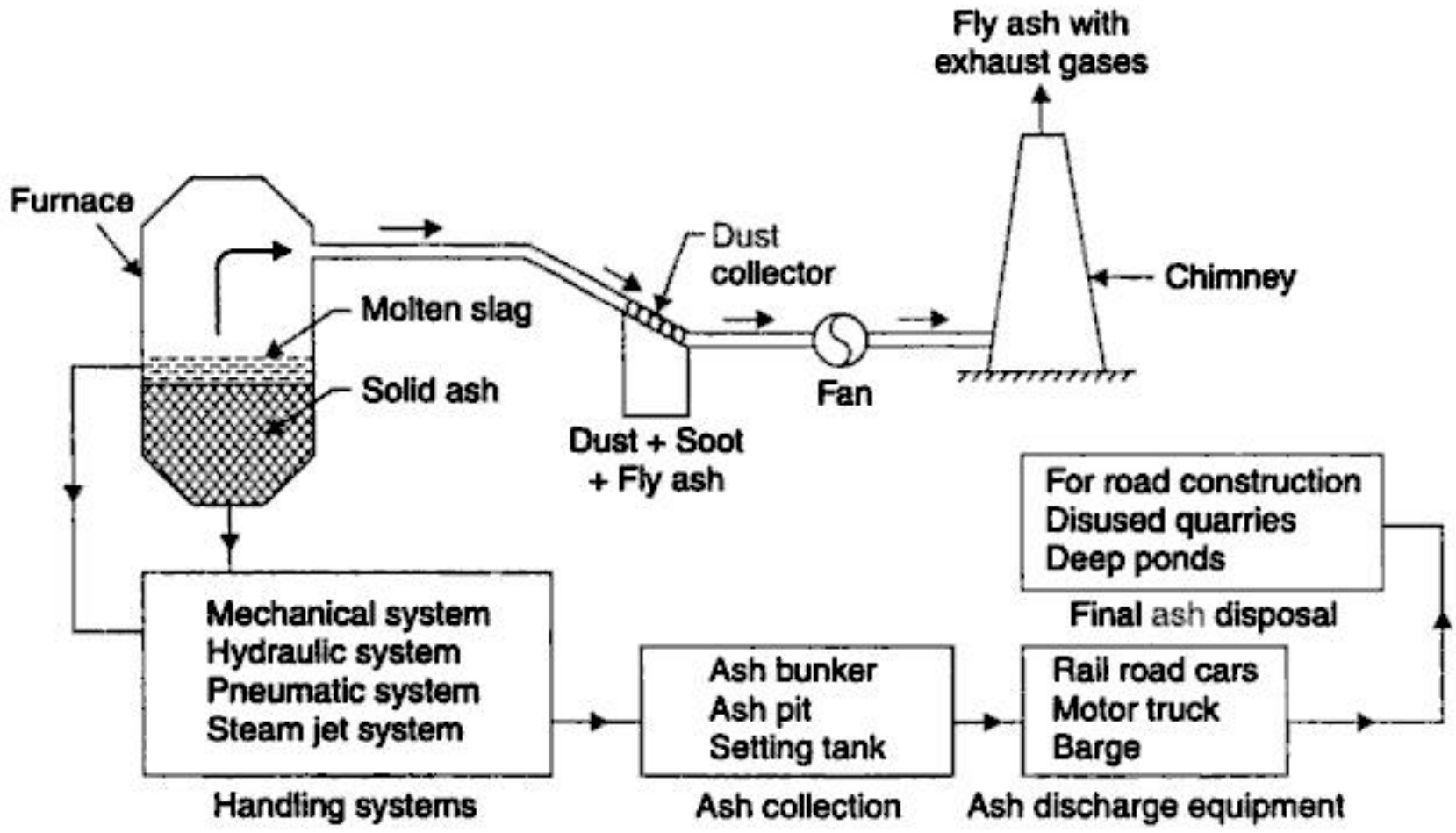

Fig. 2.25. General layout of ash handling and dust collection system.

2.13. BOILERS

2.13.1. Introduction

In simple a ***boiler*** *may be defined as a closed vessel in which steam is produced from water by combustion of fuel.*

According to American Society of Mechanical Engineers (A.S.M.E.) a *'steam generating unit'* is defined as :

"A combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vapourised".

The steam generated is employed for the following *purposes* :

(*i*) For generating power in steam engines or steam turbines.

(*ii*) In the textile industries for sizing and bleaching etc., and many other industries like sugar mills ; chemical industries.

(*iii*) For heating the buildings in cold weather and for producing hot water for hot water supply.

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The *primary requirements* of steam generators or boilers are :

(*i*) The water must be contained safely.

(*ii*) The steam must be safely delivered in desired condition (as regards its pressure, temperature, quality and required rate).

2.13.2. Classification of Boilers

The boilers may be *classified* as follows :

1. Horizontal, vertical or inclined :

If the axis of the boiler is horizontal, the boiler is called as horizontal, if the axis is vertical, it is called vertical boiler and if the axis is inclined it is known as inclined boiler. *The parts of a horizontal boiler can be inspected and repaired easily but it occupies more space. The vertical boiler occupies less floor area.*

2. Fire tube and water tube :

In the fire tube boilers, the hot gases are inside the tubes and the water surrounds the tubes. Examples : *Cochran, Lancashire* and *Locomotive boilers.*

In the water tube boilers, the water is inside the tubes and hot gases surround them. Examples : *Babcock* and *Wilcox, Stirling, Yarrow boiler etc.*

3. Externally fired and internally fired :

The boiler is known as externally fired if the fire is outside the shell. Examples : *Babcock and Wilcox boiler, Stirling boiler etc.*

In case of internally fired boilers, the furnace is located inside the boiler shell. Examples : *Cochran, Lancashire boiler etc.*

4. Forced circulation and natural circulation :

In *forced circulation* type of boilers, the circulation of water is done *by a forced pump. Examples : Velox, Lamont, Benson boiler etc.*

In *natural circulation* type of boilers, circulation of water in the boiler takes place due to *natural convention* currents produced by the application of heat. Examples : *Lancashire, Babcock* and *Wilcox boiler* etc.

5. High pressure and low pressure boilers :

The boilers which produce steam at *pressures of 80 bar and above* are called *high* pressure boilers. *Examples : Babcock* and *Wilcox, Velox, Lamont, Benson boilers.*

The boilers which produce steam at pressure *below 80 bar* are called low pressure boilers. *Examples : Cochran, Cornish, Lancashire and Locomotive boilers.*

6. Stationary and portable :

Primarily, the boilers are classified as either stationary (*land*) or mobile (*marine* and *locomotive*).

- Stationary boilers are used for power plant-steam, for central station utility power plants, for plant process steam etc.
- Mobile boilers or portable boilers include locomotive type, and other small units for temporary use at sites (just as in small coalfield pits).

7. Single tube and multi-tube boilers :

The fire tube boilers are classified as single-tube and multi-tube boilers, depending upon whether the fire tube is one or more than one. The examples of the former type are cornish, simple vertical boiler and rest of the boilers are multi-tube boilers.

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2.13.3. Comparison between 'Fire-tube and Water tube' Boilers

S. No.	Aspects	Fire-tube boilers	Water-tube boilers
1.	*Position of water and hot gases*	Hot gases inside the tubes and water outside the tubes.	Water inside the tubes and hot gases outside the tubes.
2.	*Mode of firing*	Generally internally fired.	Externally fired.
3.	*Operating pressure*	Operating pressure limited to 16 bar.	Can work under as high pressure as 100 bar.
4.	*Rate of steam production*	Lower	Higher.
5.	*Suitability*	Not suitable for large power plants.	Suitable for large power plants.
6.	*Risk on bursting*	Involves lesser risk on explosion due to lower pressure.	Involves more risk on bursting due to high pressure.
7.	*Floor area*	For a given power it occupies more floor area.	For a given power it occupies less floor-area.
8.	*Construction*	Difficult	Simple
9.	*Transportation*	Difficult	Simple
10.	*Shell diameter*	Large for same power	Small for same power
11.	*Chances of explosion*	Less	More
12.	Treatment of water	Not so necessary	More necessary
13.	*Accessibility of various parts*	Various parts not so easily accessible for cleaning, repair and inspection.	Various parts are more accessible.
14.	*Requirement of skill*	Require less skill for efficient and economic working.	Require more skill and careful attention.

2.13.4. High Pressure Boilers

In applications where steam is needed at pressure, 30 bar, and individual boilers are required to raise less than about 30000 kg of steam per hour, *shell boilers are considerably cheaper than the water-tube boilers.* Above these limits, shell boilers (generally factory built) are difficult to transport if not impossible. There are no such limits to water-tube boilers. These can be site erected from easily transportable parts, and moreover the pressure parts are of smaller diameter and therefore can be thinner. The geometry can be varied to suit a wide range of situations and furnace is not limited to cylindrical form. Therefore, *water tube boilers are generally preferred for high pressure and high output whereas shell boilers for low pressure and low output.*

The modern high pressure boilers employed for power generation are for steam capacities 30 to 650 tonnes/h and above with a pressure up to 160 bar and maximum steam temperature of about 540°C.

2.13.4.1. Unique features of high pressure boilers

Following are the *unique features* of high pressure boilers :

1. Method of water circulation
2. Type of tubing
3. Improved method of heating.

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1. *Method of water circulation.* The circulation of water through the boiler may be *natural circulation* due to density difference or *forced circulation.* In all modern high pressure boiler plants, the water circulation is maintained with the help of pump which forces the water through the boiler plant. The use of natural circulation is limited to sub-critical boilers due to its limitations.

2. *Type of tubing.* In most of the high pressure boilers, the water circulated through the tubes and their external surfaces are exposed to the flue gases. In water-tube boilers, if the flow takes place through one continuous tube, the large pressure drop takes place due to friction. This is *considerably reduced by arranging the flow to pass through parallel system of tubing.* In most of the cases, several sets of the tubings are used. This type of arrangement helps to *reduce the pressure loss,* and better control over the quality of the steam.

3. *Improved method of heating.* The following improved methods of heating may be used to increase the heat transfer :

(*i*) The saving of heat by *evaporation of water* above critical pressure of the steam.

(*ii*) The heating of water can be made by *mixing the superheated steam.* The mixing phenomenon *gives highest heat transfer co-efficient.*

(*iii*) The overall heat transfer coefficient can be increased by *increasing the water velocity inside the tube and increasing the gas velocity above sonic velocity.*

2.13.4.2. Advantages of high pressure boilers

The following are the *advantages* of high pressure boilers :

1. In high pressure boilers pumps are used to maintain forced circulation of water through the tubes of the boiler. This *ensures positive circulation of water and increases evaporative capacity of the boiler and less number of steam drums will be required.*
2. The *heat of combustion is utilised more efficiently* by the use of small diameter tubes in large number and in multiple circuits.
3. *Pressurised combustion* is used which *increases rate of firing of fuel* thus increasing the rate of heat release.
4. Due to compactness less floor space is required.
5. The tendency of scale formation is eliminated due to high velocity of water through the tubes.
6. All the parts are uniformly heated, therefore, the danger of overheating is reduced and thermal stress problem is simplified.
7. The differential expansion is reduced due to uniform temperature and this reduces the possibility of gas and air leakages.
8. The components can be arranged horizontally as high head required for natural circulation is eliminated using forced circulation. There is a greater flexibility in the components arrangement.
9. The steam can be raised quickly to meet the variable load requirements without the use of complicated control devices.
10. The *efficiency of plant is increased upto 40 to 42 percent* by using high pressure and high temperature steam.
11. A very rapid start from cold is possible if an external supply of power is available. Hence, the boiler can be used for carrying peak loads or standby purposes with hydraulic station.
12. Use of high pressure and high temperature steam is economical.

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High pressure boilers are enumerates below :

1. Lamont boiler
2. Loeffler boiler
3. Benson boiler
4. Velox boiler
5. Supercritical boilers
6. Supercharged boiler

2.14. STEAM TURBINES

2.14.1. Introduction

The **steam turbine** *is a prime-mover in which the potential energy of the steam is transformed into kinetic energy, and latter in its turn is transformed into the mechanical energy of rotation of the turbine shaft.* The turbine shaft, directly or with the help of a reduction gearing, is connected with the driven mechanism. Depending on the type of the driven mechanism a steam turbine may be *utilised in most diverse fields of industry, for power generation* and *for transport.* Transformation of the potential energy of steam into the mechanical energy of rotation of the shaft is brought about by different means.

2.14.2. Classification of Steam Turbines

There are several ways in which the steam turbines may be classified. The most important and common division being with respect to the *action of the steam*, as :

(*a*) Impulse.

(*b*) Reaction.

(*c*) Combination of impulse and reaction.

Other classifications are :

1. **According to the number of pressure stages :**

(*i*) *Single-stage turbines* with one or more velocity stages usually of small-power capacities ; these turbines are mostly used for driving centrifugal compressors, blowers and other similar machinery.

(*ii*) *Multi-stage impulse and reaction turbines* ; they are made in a wide range of power capacities varying from small to large.

2. **According to the direction of steam flow :**

(*i*) *Axial turbines* in which steam flows in a direction parallel to the axis of the turbine.

(*ii*) *Radial turbines* in which steam flows in a direction perpendicular to the axis of the turbine ; one or more low-pressure stages in such turbines are made axial.

3. **According to the number of cylinders :**

(*i*) Single-cylinder turbines.

(*ii*) Double-cylinder turbines.

(*iii*) Three-cylinder turbines.

(*iv*) Four-cylinder turbines.

Multi-cylinder turbines which have their rotors mounted on one and the same shaft and coupled to a single generator are known as *single shaft turbines* ; turbines with separate rotor shafts for each cylinder placed parallel to each other are known as ***multiaxial turbines.***

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4. According to the method of governing :

(*i*) *Turbines with throttle governing* in which fresh steam enters through one or more (depending on the power developed) simultaneously operated throttle valves.

(*ii*) *Turbines with nozzle governing* in which fresh steam enters through two or more consecutively opening regulators.

(*iii*) *Turbines with bypass governing* in which steam turbines besides being fed to the first stage is also directly fed to one, two or even three intermediate stages of the turbine.

5. According to heat drop process :

(*i*) *Condensing turbines with generators* ; in these turbines steam at a pressure less than atmospheric is directed to a condenser ; besides, steam is also extracted from intermediate stages for feed water heating, the number of such extractions usually being from 2-3 to as much 8-9. The latent heat of exhaust steam during the process of condensation is completely lost in these turbines.

(*ii*) *Condensing turbines with one or two intermediate stage extractions* at specific pressures for industrial and heating purposes.

(*iii*) *Back pressure turbines*, the exhaust steam from which is utilised for industrial or heating purposes ; to this type of turbines can also be added (in a relative sense) turbines with deteriorated vacuum, the exhaust steam of which may be used for heating and process purposes.

(*iv*) *Topping turbines* ; these turbines are also of the back pressure type with the difference that the exhaust steam from these turbines is further utilised in medium and low-pressure condensing turbines. These turbines, in general, operate at high initial conditions of steam pressure and temperature, and are mostly used during extension of power station capacities, with a view to obtain better efficiencies.

(*v*) *Back pressure turbines with steam extraction from intermediate stages at specific pressure* ; turbines of this type are meant for supplying the consumer with steam of various pressures and temperature conditions.

(*vi*) *Low pressure turbines* in which the exhaust steam from reciprocating steam engines, power hammers, etc., is utilised for power generation purposes.

(*vii*) *Mixed pressure turbines* with two or three pressure stages, with supply of exhaust steam to its intermediate stages.

6. According to steam conditions at inlet to turbine :

(*i*) *Low pressure turbines*, using steam at a pressure of 1.2 to 2 ata.

(*ii*) *Medium pressure turbines*, using steam at pressure of up to 40 ata.

(*iii*) *High pressure turbines*, utilising steam at pressures above 40 ata.

(*iv*) *Turbines of very high pressures*, utilising steam at pressures of 170 ata and higher and temperatures of 550°C and higher.

(*v*) *Turbines of supercritical pressures*, using steam at pressures of 225 ata and above.

7. According to their usage in industry :

(*i*) *Stationary turbines with constant speed of rotation* primarily used for driving alternators.

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(*ii*) *Stationary steam turbines* with variable speed meant for driving turbo-blowers, air circulators, pumps, etc.

(*iii*) *Non-stationary* turbines with variable speed ; turbines of this type are usually employed in steamers, ships and railway locomotives.

2.14.3. Advantages of Steam Turbine over the Steam Engines

The following are the principal *advantages* of steam turbine over steam engines :

1. The thermal efficiency of a steam turbine is much higher than that of a steam engine.
2. The power generation in a steam turbine is at a uniform rate, therefore necessity to use a flywheel (as in the case of steam engine) is not felt.
3. Much higher speeds and greater range of speed is possible than in case of a steam engine.
4. In large thermal stations where we need higher outputs, the steam turbines prove very suitable as these can be made in big sizes.
5. With the absence of reciprocating parts (as in steam engine) the balancing problem is minimised.
6. No internal lubrication is required as there are no rubbing parts in the steam turbine.
7. In a steam turbine there is no loss due to initial condensation of steam.
8. It can utilise high vacuum very advantageously.
9. Considerable overloads can be carried at the expense of slight reduction in overall efficiency.

2.14.4. Description of Common Types of Turbines

The common types of steam turbines are :

1. Simple Impulse turbine.
2. Reaction turbine.

The main difference between these turbines lies *in the way in which the steam is expanded while it moves through them. In the former type steam expands in the nozzles and its pressure does not alter as it moves over the blades while in the latter type the steam expands continuously as it passes over the blades and thus there is gradual fall in the pressure during expansion.*

1. Simple impulse turbine :

Fig. 2.26 shows a simple impulse turbine diagrammatically. The top portion of the figure exhibits a longitudinal section through the upper half of the turbine, the middle portion shows one set of nozzles which is followed by a ring of moving blades, while lower part of the diagram indicates approximately changes in pressure and velocity during the flow of steam through the turbine. This turbine is called *'simple'* impulse turbine since the expansion of the steam takes place in one set of the nozzles.

As the steam flows through the nozzle its pressure falls from steam chest pressure to condenser pressure (or atmospheric pressure if the turbine is non-condensing). Due to this relatively higher ratio of expansion of steam in the nozzles the steam leaves the nozzle with a very high velocity. From Fig. 2.26, it is evident that the velocity of the steam leaving the moving blades is a

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large portion of the maximum velocity of the steam when leaving the nozzle. The loss of energy due to this higher exit velocity is commonly the ***"carry over loss"*** or ***"leaving loss"***.

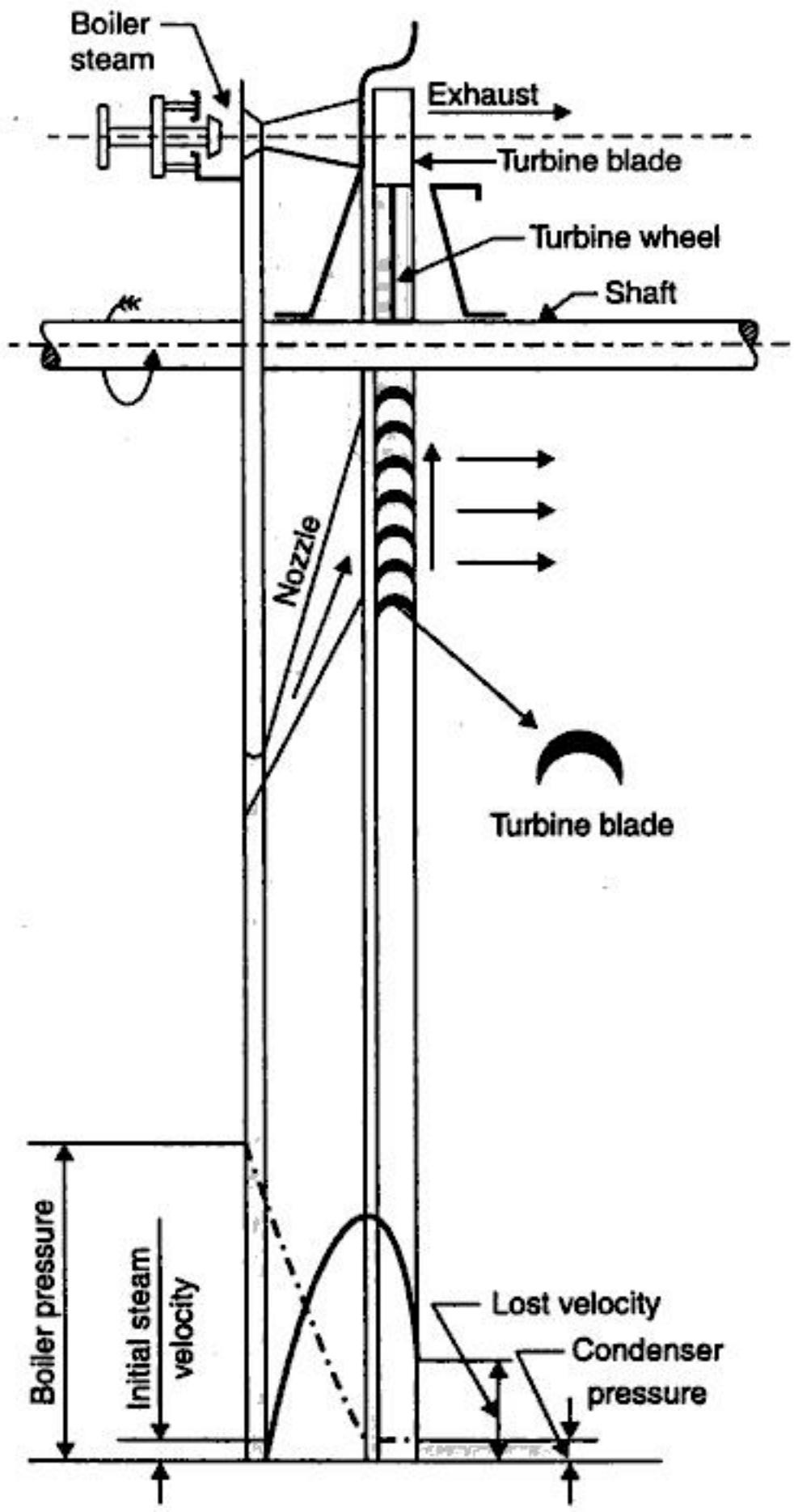

Fig. 2.26. Simple impulse turbine.

The principal example of this turbine is the well known **De laval turbine** and in this turbine the 'exit velocity' or 'leaving velocity' or 'lost velocity' may amount to 3.3 per cent of the nozzle outlet velocity. Also since all the kinetic energy is to be absorbed by one ring of the moving blades only, the velocity of wheel is too high (varying from 25,000 to 30,000 r.p.m.). This wheel or rotor speed, however, can be reduced by different methods (discussed in the following article).

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2.14.6. Difference Between Impulse and Reaction Turbines

S. No.	Aspects	Impulse turbine	Reaction turbine
1.	*Pressure drop*	Only in nozzles and not in moving blades.	In fixed blades (nozzles) as well as in moving blades.
2.	*Area of blade channels*	Constant.	Varying (converging type).
3.	*Blades*	Profile type.	Aerofoil type.
4.	*Admission of steam*	Not all round or complete.	All round or complete.
5.	*Nozzles / fixed blades*	Diaphram contains the nozzle.	Fixed blades similar to moving blades attached to the casing serve as nozzles and guide the steam.
6.	*Power*	Not much power can be developed.	Much power can be developed.
7.	*Space*	Requires less space for same power.	Requires more space for same power.
8.	*Efficiency*	Low.	High.
9.	*Suitability*	Suitable for small power requirements.	Suitable for medium and higher power requirements.
10.	*Blade manufacture*	Not difficult.	Difficult.

2.14.7. Steam Turbine Governing and Control

The objective of governing is to keep the turbine speed fairly constant irrespective of load. The principal methods of steam turbine governing are as follows :

1. Throttle governing
2. Nozzle governing
3. By-pass governing
4. Combination of 1 and 2 and 1 and 3.

2.15. STEAM CONDENSERS

2.15.1. Introduction

A steam condenser *is a device or an appliance in which steam condenses and heat released by steam is absorbed by water*. It serves the following *purposes :*

1. It *maintains a very low back pressure* on the exhaust side of the piston of the steam engine or turbine. Consequently, the steam expands to a greater extent which results in an *increase in available heat energy* for converting into mechanical work. The shaded area in Fig. 2.31. (*i.e.*, area 44'5'5) shows the increase in work obtained by fitting a condenser to a non-condensing engine. *The thermal efficiency of a condensing unit therefore is higher than that of non-condensing unit for the same available steam.*
2. It supplies to the boiler pure and hot feed water as the condensed steam which is discharged from the condenser and collected in a hot well, can be used as feed water for the boiler.

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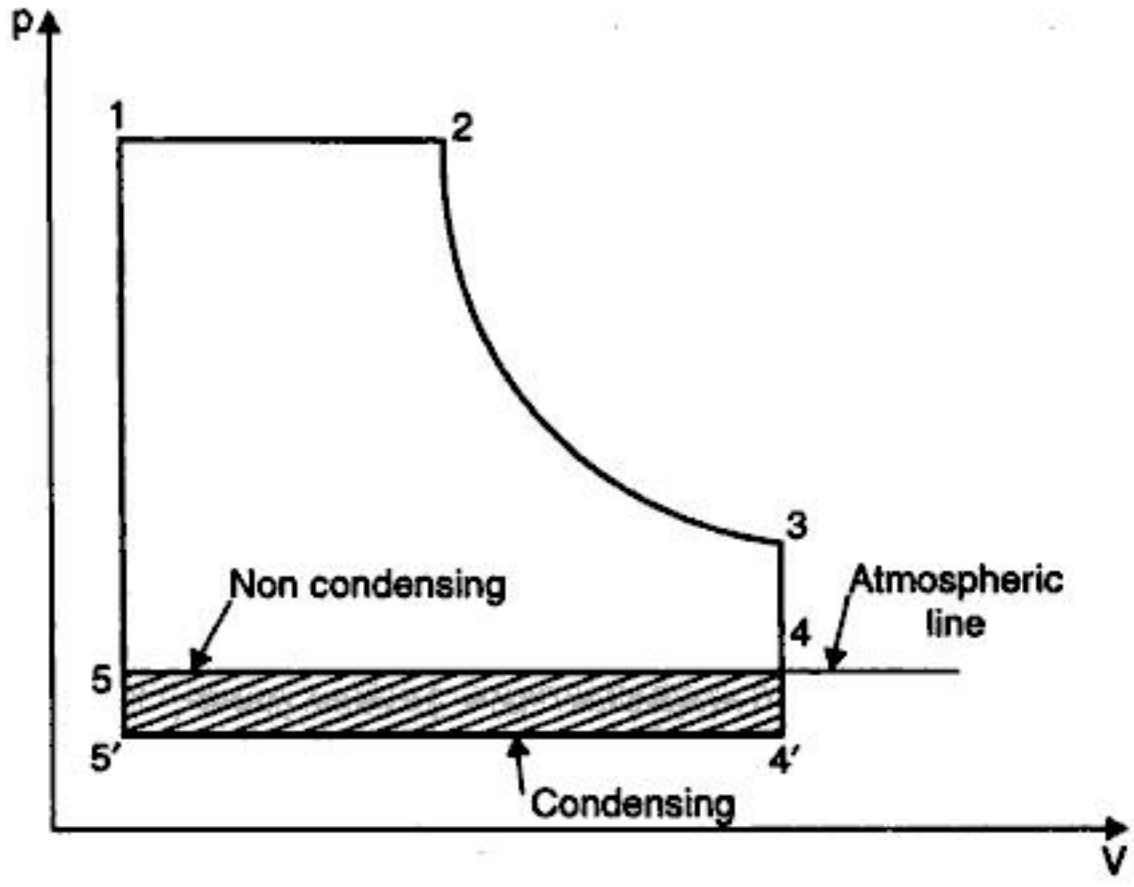

Fig. 2.31

2.15.2. Vacuum

***Vacuum** is sub-atmospheric pressure.* It is measured as the pressure depression below atmospheric. The condensation of steam in a closed vessel produces a partial vacuum by reason of the great reduction in the volume of the low pressure steam or vapour. The back pressure in steam engine or steam turbine can be lowered from 0.013 to 0.2 bar abs. or even less. Since the steam engines are intermittent flow machines and as such cannot take the advantage of a very low vacuum, therefore, for most steam engines the exhaust pressure is about 0.2 to 0.28 bar abs. On the other hand, in steam turbines, which are continuous flow machines, the back pressure may be about 0.025 bar abs.

2.15.3. Organs of a Steam Condensing Plant

A steam condensing plant mainly consists of the following *organs / elements* :

1. Condenser (to condense the steam).
2. Supply of cooling (or injection) water.
3. Wet air pump (to remove the condensed steam, the air and uncondensed water vapour and gases from the condenser ; separate pumps may be used to deal with air and condensate).
4. Hot well (where the condensate can be discharged and from which the boiler feed water is taken).
5. Arrangement for recooling the cooling water in case surface condenser is employed.

2.15.4. Classification of Condensers

Mainly, condensers are of two types : (1) Jet condensers, (2) Surface condensers.

In ***jet condensers,*** *the exhaust steam and water come in direct contact with each other* and temperature of the condensate is the same as that of cooling water leaving the condenser. The cooling water is usually sprayed into the exhaust steam to cause rapid condensation.

In ***surface condensers,*** *the exhaust steam and water do not come into direct contact.* The steam passes over the outer surface of tubes through which a supply of cooling water is maintained.

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There may be single-pass or double-pass. In single-pass condensers, the water flows in one direction only through all the tubes, while in two-pass condenser the water flows in one direction through the tubes and returns through the remainder.

A jet condenser is simpler and cheaper than a surface condenser. It should be installed when the cooling water is cheaply and easily made suitable for boiler feed or when a cheap source of boiler and feed water is available. *A surface condenser is most commonly used because the condensate obtained is not thrown as a waste but returned to the boiler.*

2.15.5. Jet Condensers

These condensers may be classified as :

(*a*) Parallel-flow type

(*b*) Counter-flow type

(*c*) Ejector type.

Parallel flow and counter flow condensers are further sub-divided into two types : (*i*) Low level type (*ii*) High level type.

In *parallel-flow type* of condenser, both the exhaust steam and cooling water find their entry at the top of the condenser and then flow downwards and condensate and water are finally collected at the bottom.

In *counter-flow type,* the steam and cooling water enter the condenser from opposite directions. Generally, the exhaust steam travels in upward direction and meet the cooling water which flows downwards.

2.15.6. Surface Condensers

Most condensers are generally classified on the direction of flow of condensate, the arrangement of the tubing and the position of the condensate extraction pump. The following is the main classification of surface condensers :

(*i*) Down flow type

(*ii*) Central flow type

(*iii*) Inverted flow type

(*iv*) Regenerative type

(*v*) Evaporative type.

2.15.7. Comparison Between Jet and Surface Condensers

S. No.	Jet Condenser	Surface Condenser
1.	Low manufacturing cost.	High manufacturing cost.
2.	Lower up keep.	Higher upkeep.
3.	Requires small floor space.	Requires large floor space.
4.	The condensate cannot be used as feed water in the boilers unless the cooling water is free from impurities.	Condensate can be reused as feed water as it does not mix with the cooling water.
5.	More auxiliary power required.	Less auxiliary power needed.

2.16. FEED WATER TREATMENT

For steam power plants water is one of the most important raw materials. In most of the cases, water used for steam power plants contains impurities which must be treated before use. All natural waters—even rain, snow, hail, treated municipal supplies contain impurities in one form or the other.

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2.16.1. Classification of Impurities in Water

The impurities in water may be classified as follows :

1. Visible impurities :

(*i*) *Microbiological growth.* Presence of micro-organisms is always undesirable as they may produce *clogging troubles.*

(*ii*) *Turbidity and sediments. Turbidity* is the suspended insoluble matter whereas *sediments* are the coarse particles which settle down in stationary water, both are objectionable.

2. Dissolved gases :

(*i*) Carbondioxide
(*ii*) Oxygen
(*iii*) Nitrogen
(*iv*) Methane
(*v*) Hydrogen sulphide.

3. Minerals and salts :

(*i*) Iron and manganese
(*ii*) Sodium and potassium salts
(*iii*) Flourides
(*iv*) Silica.

4. Mineral acids. Their presence in water is always undesirable as it may result in the chemical reaction with the boiler material.

5. Hardness. The salts of calcium and magnesium as bicarbonates, chlorides, sulphates etc. are mainly responsible for the formation of a *very hard surface which resists heat transfer and clogs the passages in pipes.* Presence of these salts is known as *hardness.*

2.16.2. Troubles Caused by the Impurities in Water

The impurities in water may cause one or more of the following troubles :

1. Scale formation
2. Corrosion
3. Carry over
4. Embrittlement.

2.16.3. Methods of Feed Water Treatment

The different treatments adopted to remove the various impurities are enumerated below :

1. Mechanical treatment :

(*i*) Sedimentation
(*ii*) Coagulation
(*iii*) Filteration
(*iv*) Interior painting.

2. Thermal treatment :

(*i*) Deaeration
(*ii*) Distillation by evaporators.

3. Chemical treatment :

(*i*) Cold lime-soda softening process
(*ii*) Hot lime-soda softening process
(*iii*) Lime-phosphate softening process
(*iv*) Ion exchange process which may be sodium zeolite process or hydrogen zeolite process.

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4. Demineralisation.

5. Blow down :

(*i*) Hot lime-soda and hot zeolite process

(*ii*) Adding acid to control alkalinity and *vice-versa*.

2.17. ADVANTAGES AND DISADVANTAGES OF STEAM POWER PLANTS

Advantages of Steam power plants :

1. They can respond to rapidly changing loads without difficulty.
2. A portion of the steam generated can be used as a process steam in different industries.
3. Can be located very conveniently near the load centre.
4. As these plants can be set up near the industry transmission costs are reduced.
5. Steam engines and turbines can work under 25 per cent of overload continuously.
6. Fuel used is cheaper.
7. Less space is required in comparison with that for hydro-electric plants.
8. Cheaper in production cost in comparison with that of diesel power stations.
9. Cheaper in initial cost in comparison with that of diesel power stations.

Disadvantages :

1. Maintenance and operating costs are high.
2. The cost of plant increases with increase in temperature and pressure.
3. Long time required for erection and putting into action.
4. A large quantity of water is required.
5. Great difficulty experienced in coal handling.
6. The plant efficiency decreases rapidly below about 75 per cent load.
7. Presence of troubles due to smoke and heat in the plant.

2.18. MISCELLANEOUS

2.18.1. Useful Life of Steam Power Plant Components

Approximate useful life of some of the components of a steam power plant is given below :

Components	Life (years)
1. Water tube boiler	20
2. Coal and ash machinery	10 to 20
3. Steam turbines	15 to 20
4. Steam condensers	20
5. Turbo-generators	10 to 20
6. Feed water heater	30
7. Pumps	15 to 20
8. Transformers	15 to 20
9. Motors	20
10. Air compressors	20 to 25
11. Buildings	50

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2.18.2. Steam Power Plant Pumps

The pumps used in a steam power plant are *classified* as follows :

1. *Reciprocating* :
   (*i*) Direct acting (*ii*) Power.
2. *Rotary* :
   (*i*) Vane (*ii*) Screw
   (*iii*) Gear (*iv*) Lobe.
3. *Centrifugal* :
   (*i*) Volute (*ii*) Diffuser
   (*iii*) Axial flow (*iv*) Mixed flow.

The above mentioned pumps are used for the following *services* :

(*i*) Boiler feed (*ii*) Circulating water
(*iii*) Evaporator feed (*iv*) Condensate
(*v*) Well water (*vi*) Ash sluicing
(*vii*) Fuel oil.

2.18.3. Cost of Steam Power Plant

A typical subdivision of investment cost of steam power station is as follows :

Components	*Investment cost*
1. Building etc.	25%
2. Boiler Plant	18%
3. Turbo-generators and condensers	25%
4. Fuel handling	6%
5. Switch yard, switching and wiring	16%
6. Piping	5%
7. Miscellaneous	5%

2.18.4. Comparison of Various types of Power Plants

S. No.	Particulars	Steam power plants	Hydro-electric power plants	Diesel power plants	Nuclear power plants
1.	*Site*	Located near load centres but other factors water supply, land cost, transportation facilities are to be kept in view. Location of steam power plant is somewhat flexible as compared with that of hydro-plants.	The site should be such that sufficient area, huge quantity of water at a sufficient head, cheap and rocky land and transportation facilities should be available. These plants are usually at a far off distance from the load centres.	Can be installed anywhere.	Located near the load centre.

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2.	*Initial cost*	*Low* as compared to hydroelectric and atomic power plants.	*High* as compared to steam power plant on account of large amount of excavation work and heavy cost of transportation of the plant and machinery.	Initial cost is the *minimum*.	The capital cost is *very high* as compared to all other types of power plants on account of heavy cost of nuclear reactors and heavy cost of erection as highly specialised and expert engineers are required for its erection work.
3.	*Fuel transportation cost*	*High*, especially when the power plants are away from the coal mines and has no railway siding.	*Nil* (as no fuel is required).	Higher than that of atomic power plant but lower than that for steam power plants.	Very low (since quantity of fuel required is very small).
4.	*Operating cost*	Very high as compared to hydro-plants and atomic power plants but low as compared to diesel power plant.	Practically nil (since no fuel is required for the operation of the plant).	Very high as compared to all other types of power plants.	Very low as compared to all other types of power plants except that of hydro-electric plants.
5.	*Maintenance cost*	Higher as compared with that of hydro-plants and diesel power plants (because large operating staff and more skilled engineers are required).	Maintenance cost is comparatively low (because few skilled engineers and small operating staff is required).	Maintenance cost is comparatively lower (because lesser operating and supervising staff is required).	Maintenance cost is comparatively higher (because skilled and well trained staff is required for its operation and maintenance).
6.	*Limit of source of power*	Source of fuel *i.e., coal* reserve all over the world is considered to be fixed and therefore coal mines are being exhausted and time may come when all of these might get exhausted.	Source of power *i.e., water* in case of hydro-plants is not dependable because it depends upon the rainfall which is at the whim of nature.	Source of fuel *i.e., diesel* is not available in plenty.	The source of power is unlimited since large deposits of fissionable materials all over the world are available.
7.	*Transmission and distribution cost.*	Low (because short transmission lines are required).	*Very high* (because long transmission lines are required).	Transmission cost is *nil* and distribution cost is also *very small*.	*Very low.*

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8.	*Reliability*	Less reliable.	More reliable.	Less reliable.	Reliable.
9.	*Simplicity and cleanliness*	Atmosphere is polluted by fumes and residues of pulverised fuels.	Most simple and clean.	Simple and clean than steam plants and atomic power plants.	The handling of atomic power plant is quite complicated as radiation hazards are involved in it. Special outfits are designed and explored by the operating staff.
10.	*Field of application*	Most economical if sited near coal mines and by the side of river or canal.	Most economical where water source is available at a sufficient head.	These plants are installed to supply power is emergency.	Where neither water nor coal as a source of power is available, as in Rajasthan these plants are more feasible and adopted.
11.	*Standby losses*	Maximum as the boiler remains in operation even when the turbine is not working.	No standby losses.	Less standby losses.	Less standby losses.

2.18.5. Thermal Power Stations in India

Some of the thermal power stations installed in the country or under the process of installation are as follows :

S. No.	State	Name of power station	Capacity (MW)
1.	Andhra Pradesh	Kothagndam	240
2.	Assam	Gauhati	40
3.	Bihar	(*i*) Barauni	140
		(*ii*) Bokaro	225
		(*iii*) Patratu	400
4.	Delhi	(*i*) Rajghat and I.P. thermal power station	350
		(*ii*) Badarpur	300
5.	Gujrat	(*i*) Dhuvaran	530
		(*ii*) Ukai	240
6.	Haryana	(*i*) Faridabad	200
		(*ii*) Panipat	220
7.	Madhya Pradesh	(*i*) Kobra	420
		(*ii*) Satpura	300
		(*iii*) Amarkantak	180
8.	Maharashtra	(*i*) Nagpur (Koradi)	480
		(*ii*) Nasik	280
		(*iii*) paras	90

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6. Pulverised fuel burners are classified as follows :
   (*i*) Long flame burners (*ii*) Turbulent burners
   (*iii*) Tangential burners (*iv*) Cyclone burners.
7. Oil burners are classified as follows :
   1. Vapourising oil burners :
      (*a*) Atmospheric pressure atomising burner (*b*) Rotating cup burner
      (*c*) Recirculating burner (*d*) Wick type burner.
   2. Atomising fuel burners :
      (*a*) Mechanical or oil pressure atomising burner
      (*b*) Steam or high pressure atomising burner
      (*c*) Low pressure air atomising burner.
8. Fluidised bed may be defined as the bed of solid particles behaving as a fluid.
9. Ash handling systems may be classified as follows :
   (*i*) Mechanical handling system (*ii*) Hydraulic system
   (*iii*) Pneumatic system (*iv*) Steam jet system.
10. The dust collectors may be classified as follows :
    1. Mechanical just collectors
       (*i*) Wet type (scrubbers)
          (*a*) Spray type (*b*) Packed type
          (*c*) Impingement type.
       (*ii*) Dry type
          (*a*) Gravitational separators (*b*) Cyclone separators.
    2. Electrical dust collectors
       (*i*) Rod type (*ii*) Plate type.
11. The 'collection efficiency' of a dust collector is the amount of dust removed per unit weight of dust.
12. pH value of water is the logarithm of the reciprocal of hydrogen ion concentration. It is number from 0 to 14 with 7 indicating neutral number.
13. The small pressure difference which causes a flow of gas to take place is termed as a *draught*.
14. The most important classification of steam turbines is as follows :
    (*i*) Impulse turbines (*ii*) Reaction turbines
    (*iii*) Combination of impulse and reaction turbines.

THEORETICAL QUESTIONS

1. How are steam power plants classified ?
2. Give the layout of a modern steam power plant and explain it briefly.
3. What are the essential requirements of steam power station design ?
4. What factors should be taken into consideration while selecting the site for steam power plant ?
5. How can the capacity of a steam power plant be determined ?
6. On factors does the choice of steam conditions depend ?
7. Enumerate the means by which the coal from coal mines can be transported.
8. What are the requirements of good coal handling plant ?
9. Enumerate and explain the steps involved in handling of the coal.
10. Explain with the help of a neat diagram the arrangement of the Fluidised Bed Combustion (FBC) system.
11. State the characteristics of a good ash handling plant.
12. Enumerate and explain various modern ash-handling systems.
13. How are dust collectors classified ?
14. Explain with the help of a diagram the working of a 'cyclone separator'.

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15. How do you define the 'collection efficiency' of a dust separator ?
16. What are the uses of ash and dust ?
17. Give the general layout of ash handling and dust collection system.
18. Discuss various methods of compounding steam turbines ?
19. Describe briefly the various methods of 'steam turbine governing'.
20. Define a steam condenser and state its functions.
21. Explain the reasons for inefficiency in surface condensers.
22. Explain the effects of air leakage in a condenser.
23. List the advantages and disadvantages of steam power plants.
24. Give comparison between steam, hydro-electric, diesel and nuclear power plants.

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3

Diesel Engine Power Plant

3.1. Introduction. 3.2. Advantages and disadvantages of diesel power plants. 3.3. Applications of diesel power plant. 3.4. Site selection. 3.5. Heat engines. 3.6. Classification of I.C. engines. 3.7. Comparison between a petrol engine and a diesel engine. 3.8. Essential components of a diesel power plant : engine, air intake system, exhaust system, fuel system. 3.9. Operation of a diesel power plant. 3.10. Types of diesel engines used for diesel power plants. 3.11. Layout of a diesel engine power plant. Highlights—Theoretical Questions.

3.1. INTRODUCTION

- Diesel engine power plants are installed *where supply of coal and water is not available in sufficient quantity* or *where power is to be generated in small quantity* or *where standby sets are required for continuity of supply such as in hospitals, telephone exchanges, radio stations and cinemas.* These plants in the range of 2 to 50 MW capacity are used as *central stations* for supply authorities and works and they are universally adopted to supplement hydro-electric or thermal stations where standby generating plants are essential for starting from cold and under emergency conditions.
- In several countries, the demand for diesel power plants is increased for electric power generation because of difficulties experienced in construction of new hydraulic plants and enlargement of old hydro-plants. A long term planning is required for the development of thermo and hydro-plants which cannot keep the pace with many times the increased demand by the people and industries.
- The diesel units used for electric generation are *more reliable* and *long-lived piece of equipment* compared with other types of plants.

3.2. ADVANTAGES AND DISADVANTAGES OF DIESEL POWER PLANTS

The *advantages and disadvantages* of diesel power plants are listed below :

Advantages :

1. Design and installation are very simple.
2. Can respond to varying loads without any difficulty.
3. The standby losses are less.
4. Occupy less space.
5. Can be started and put on load quickly.
6. Require less quantity of water for cooling purposes.
7. Overall capital cost is lesser than that for steam plants.
8. Require less operating and supervising staff as compared to that for steam plants.
9. The efficiency of such plants at part loads does not fall so much as that of a steam plant.
10. The cost of building and civil engineering works is low.
11. Can burn fairly wide range of fuels.

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12. These plants can be located very near to the load centres, many times in the heart of the town.
13. No problem of ash handling.
14. The lubrication system is more economical as compared with that of a steam power plant.
15. The diesel power plants are *more efficient than steam power plants* in the range of 150 MW capacity.

Disadvantages :

1. High operating cost.
2. High maintenance and lubrication cost.
3. Diesel units capacity is limited. These cannot be constructed in large size.
4. In a diesel power plant noise is a serious problem.
5. Diesel plants cannot supply overloads continuously whereas steam power plant can work under 25% overload continuously.
6. The diesel power plants are not economical where fuel has to be imported.
7. The life of a diesel power plant is quite small (2 to 5 years or less) as compared to that of a steam power plant (25 to 30 years).

3.3. APPLICATIONS OF DIESEL POWER PLANT

The diesel power plants find wide application in the following fields :

1. Peak load plant
2. Mobile plants
3. Standby units
4. Emergency plant
5. Nursery station
6. Starting stations
7. Central stations—where capacity required is small (5 to 10 MW)
8. Industrial concerns where power requirement is small say of the order of 500 kW, diesel power plants become more economical due to their higher overall efficiency.

3.4. SITE SELECTION

The following factors should be considered while *selecting the site for a diesel power plant* :

1. Foundation sub-soil condition. The conditions of sub-soil should be such that a foundation at a reasonable depth should be capable of providing a strong support to the engine.

2. Access to the site. The site should be so selected that it is accessible through rail and road.

3. Distance from the load centre. The location of the plant should be near the load centre. This reduces the cost of transmission lines and maintenance cost. The power loss is also minimised.

4. Availability of water. Sufficient quantity of water should be available at the site selected.

5. Fuel transportation. The site selected should be near to the source of fuel supply so that transportation charges are low.

3.5. HEAT ENGINES

Any type of engine or machine which derives heat energy from the combustion of fuel or any other sources and converts this energy into mechanical work is termed as a **heat engine.**

Heat engines may be classified into two main classes as follows :

1. External Combustion Engines.
2. Internal Combustion Engines.

1. External combustion engines (E.C. engines). In this case, *combustion of fuel takes place outside the cylinder* as in case of *steam engines* where the heat of combustion is employed to

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3.8.3. Exhaust System

Refer to Fig. 3.3. The purpose of the exhaust system is to discharge the engine exhaust to the atmosphere outside the building. The exhaust manifold connects the engine cylinder exhausts outlets to the exhaust pipe which is provided with a muffler to reduce pressure in the exhaust line and eliminate most of the noise which may result if gases are discharged directly into the atmosphere.

The exhaust pipe leading out of the building should be short in length with minimum number of bends and should have one or two flexible tubing sections which take up the effects of expansion, and isolate the system from the engine vibration. Every engine should be provided with its independent exhaust system.

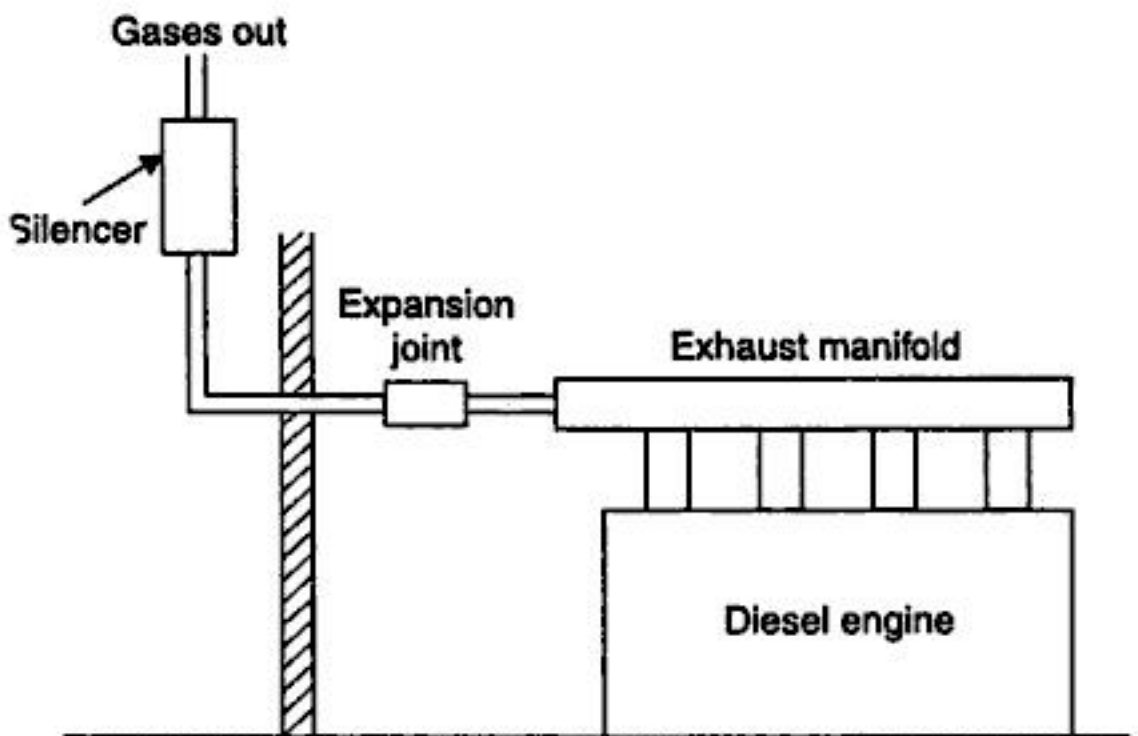

Fig. 3.3. Exhaust system.

The waste heat utilisation in a *diesel-steam* station may be done by providing waste-heat boilers in which most of the heat of exhaust gases from the engine is utilised to raise low pressure steam. Such application is common on *marine plants*. On the *stationary power plant* the heat of exhaust may be utilised to heat water in gas-to-water heat exchangers consisting of a water coil placed in exhaust muffler and using the water in the plant suitably. If air heating is required, the exhaust pipe from the engine is surrounded by the cold air jacket, and transfers the heat of exhaust gases to the air.

3.8.4. Fuel System

Refer to Fig. 3.4.

The fuel oil may be delivered at the plant site by trucks, railroad tank cars or barge and tankers. From tank car or truck the delivery is through the unloading facility to main storage tanks and then by transfer pumps to small service storage tanks known as *engine day tanks*. Large storage capacity allows purchasing fuel when prices are low. The main flow is made workable and practical by arranging the piping equipment with the necessary heaters, by passes, shut-offs, drain lines, relief valves, strainers and filters, flow meters and temperature indicators. The actual flow plans depend on type of fuel, engine equipment, size of the plant etc. The tanks should contain manholes for internal access and repair, fill lines to receive oil, vent lines to discharge vapours, overflow return lines for controlling oil flow and a suction line to withdraw oil. *Coils heated by hot water or steam reduce oil viscosity to lower pumping power needs.*

The minimum storage capacity of at least a month's requirement of oil should be kept in bulk, but where advantage of seasonal fluctuations in cost of oil is to be availed, it may be necessary to

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provide storage for a few month's requirements. *Day tanks* supply the daily fuel need of engines and may contain a minimum of about 8 hours of oil requirement of the engines. These tanks are usually placed high so that oil may flow to engines under gravity.

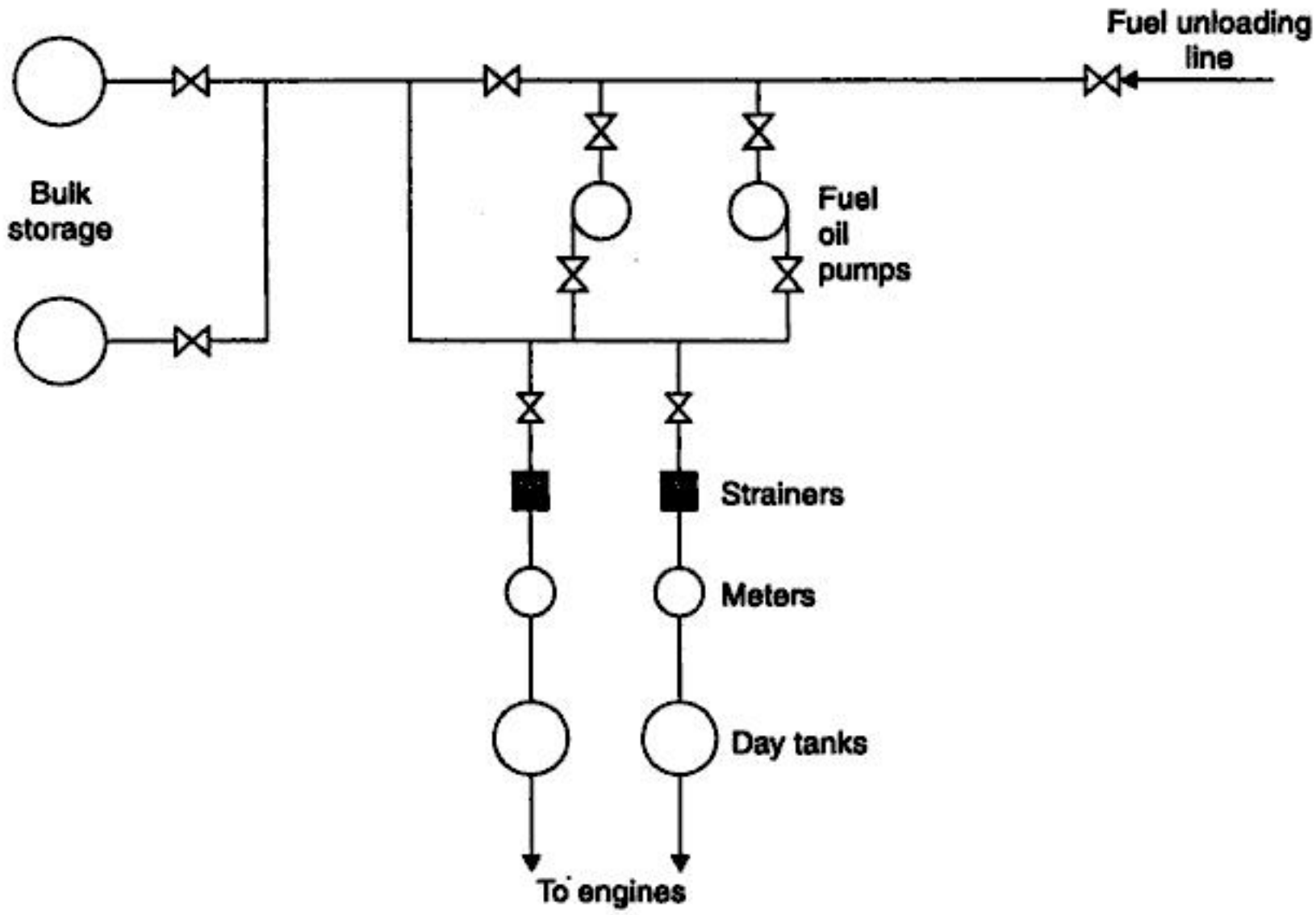

Fig. 3.4. System of fuel storage for a diesel power plant.

For satisfactory operation of a fuel oil supply system the following points should be taken care of :

1. There should be provisions for cleanliness and for changing over of lines during emergencies.
2. In all suction lines the pipe joints should be made tight.
3. Before being covered, all oil lines should be put under air pressure and the joints tested with soap solution. Small air leaks into the line can be the source of exasperating operating difficulties and are hard to remedy once the plant is in operation.
4. The piping between filter and the engine should be thoroughly oil flushed before being first placed in service.
5. Considerable importance should be given for cleanliness in handling bulk fuel oil. Dirt particles will ruin the fine lap of injection pumps or plug the injection nozzle orifices. So *high-grade filters* are of paramount importance to the diesel oil supply system.

3.8.4.1. Fuel injection system

The mechanical heart of the Diesel engine is the *fuel injection system*. The engine can perform no better than its fuel injection system. A very small quantity of fuel must be measured out, injected, atomised, and mixed with combustion air. The mixing problem becomes more difficult—the larger the cylinder and faster the rotative speed. Fortunately the high-speed engines are the small-bore automotive types ; however, special combustion arrangements such as precombustion chambers, air cells, etc., are necessary to secure good mixing. *Engines driving electrical generators have lower speeds and simple combustion chambers.*

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3.8.4.2. Functions of a fuel injection system

1. Filter the fuel.
2. Meter or measure the correct-quantity of fuel to be injected.
3. Time the fuel injection.
4. Control the rate of fuel injection.
5. Automise or break up the fuel to fine particles.
6. Properly distribute the fuel in the combustion chamber.

The injection systems are manufactured with great accuracy, especially the parts that actually meter and inject the fuel. Some of the tolerances between the moving parts are very small of the order of *one micron*. Such closely fitting parts require special attention during manufacture and hence the injection systems are *costly*.

3.8.4.3. Types of fuel injection systems

The following fuel injection systems are commonly used in diesel power station :

1. Common-rail injection system.
2. Individual pump injection system.
3. Distributor.

Atomisation of fuel oil has been secured by (*i*) *air blast* and (*ii*) *pressure spray*. Early diesel engines used air fuel injection at about 70 bar. This is sufficient not only to inject the oil, but also to atomise it for a rapid and thorough combustion. The expense of providing an air compressor and tank lead to the development of "*solid*" injection, using a liquid pressure of between 100 and 200 bar which is sufficiently high to atomise the oil it forces through spray nozzles. Great advances have been made in the field of solid injection of the fuel through research and progress in fuel pump, spray nozzles, and combustion chamber design.

3.9. OPERATION OF A DIESEL POWER PLANT

When diesel alternator sets are put in parallel, "*hunting*" or "*phase swinging*" may be produced *due to resonance* unless due care is taken in the design and manufacture of the sets. This condition occurs *due to resonance between the periodic disturbing forces of the engine and natural frequency of the system.* The engine forces result from uneven turning moment on the engine crank which are corrected by the flywheel effect. "*Hunting*" *results from the tendency of each set trying to pull the other into synchronism* and is characterised by flickering of lights.

To ensure *most economical operation of diesel engines* of different sizes when working together and sharing load it is necessary that they should carry the same percentage of their full load capacity at all times as the fuel consumption would be lowest in this condition. For best operation performance the manufacturer's recommendations should be strictly followed.

In order to get good performance of a diesel power plant the following points should be taken care of :

1. It is necessary to maintain the *cooling temperature* within the prescribed range and use of very cold water should be avoided. The cooling water should be free from suspended impurities and suitably treated to be scale and corrosion free. If the ambient temperature approaches freezing point, the cooling water should be drained out of the engine when it is kept idle.

2. During operation the *lubrication system* should work effectively and requisite pressure and temperature maintained. The engine oil should be of the correct specifications and should be in a fit condition to lubricate the different parts. A watch may be kept on the consumption of lubricating oil as this gives an indication of the true internal condition of the engine.

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3. *The engine should be periodically run even when not required to be used and should not be allowed to stand idle for more than 7 days.*

4. *Air filter, oil filters and fuel filters* should be periodically serviced or replaced as recommended by the manufacturers or if found in an unsatisfactory condition upon inspection.

5. Periodical checking of engine compression and firing pressures and also exhaust temperatures should be made.

- The engine exhaust usually provides a good indication of satisfactory performance of the engine. *A black smoke in the exhaust is a sign of inadequate combustion or engine overlocding.*
- *The loss of compression resulting from wearing out of moving parts lowers the compression ratio causing inadequate combustion.* These defects can be checked by taking *indicator diagrams* of the engine after reasonable intervals.

3.10. TYPES OF DIESEL ENGINES USED FOR DIESEL POWER PLANTS

The diesel engines may be four-stroke or two stroke cycle engines. *The two-stroke cycle engines are favoured for diesel power plants.*

Efforts are being made to use *"dual fuel engines"* in diesel power plants for better economy and proper use of available gaseous fuels in the country. The gas may be a waste product as in the case of sewage treatment installations or oil fuels where the economic advantage is self evident. With the wider availability of natural gas, the dual fuel engines may become an attractive means of utilising gas as fuel at off-peak tariffs for the electric power generation.

Working of Dual Fuel Engines :

The various strokes of a dual fuel engine are as follows :

1. Suction stroke. During this stroke *air and gas are drawn* in the engine cylinder.

2. Compression stroke. During this stroke the pressure of the mixture drawn is increased. Near the end of this stroke the *'pilot oil' is injected into the engine cylinder. The compression heat first ignites the pilot oil* and then gas mixture.

3. Working/power stroke. During this stroke the gases (at high temperature) expand and thus power is obtained.

4. Exhaust stroke. The exhaust gases are released to the atmosphere during the stroke.

3.11. LAYOUT OF A DIESEL ENGINE POWER PLANT

Fig. 3.5 shows the layout of a diesel engine power plant.

The most common arrangement for diesel engines is with parallel centre lines, with some room left for extension in future. The repairs and usual maintenance works connected with such engines necessitate sufficient space around the units and consideration should be given to the need for dismantling and removal of large components of the engine generator set. The air intakes and filters as well as the exhaust mufflers are located outside the building or may be separated from the main engine room by a partition wall. The latter arrangement is not vibration free. Adequate space for oil storage and repair shop as well as for office should be provided close to the main engine room. Bulk storage of oil may be outdoor. The engine room should be well ventilated.

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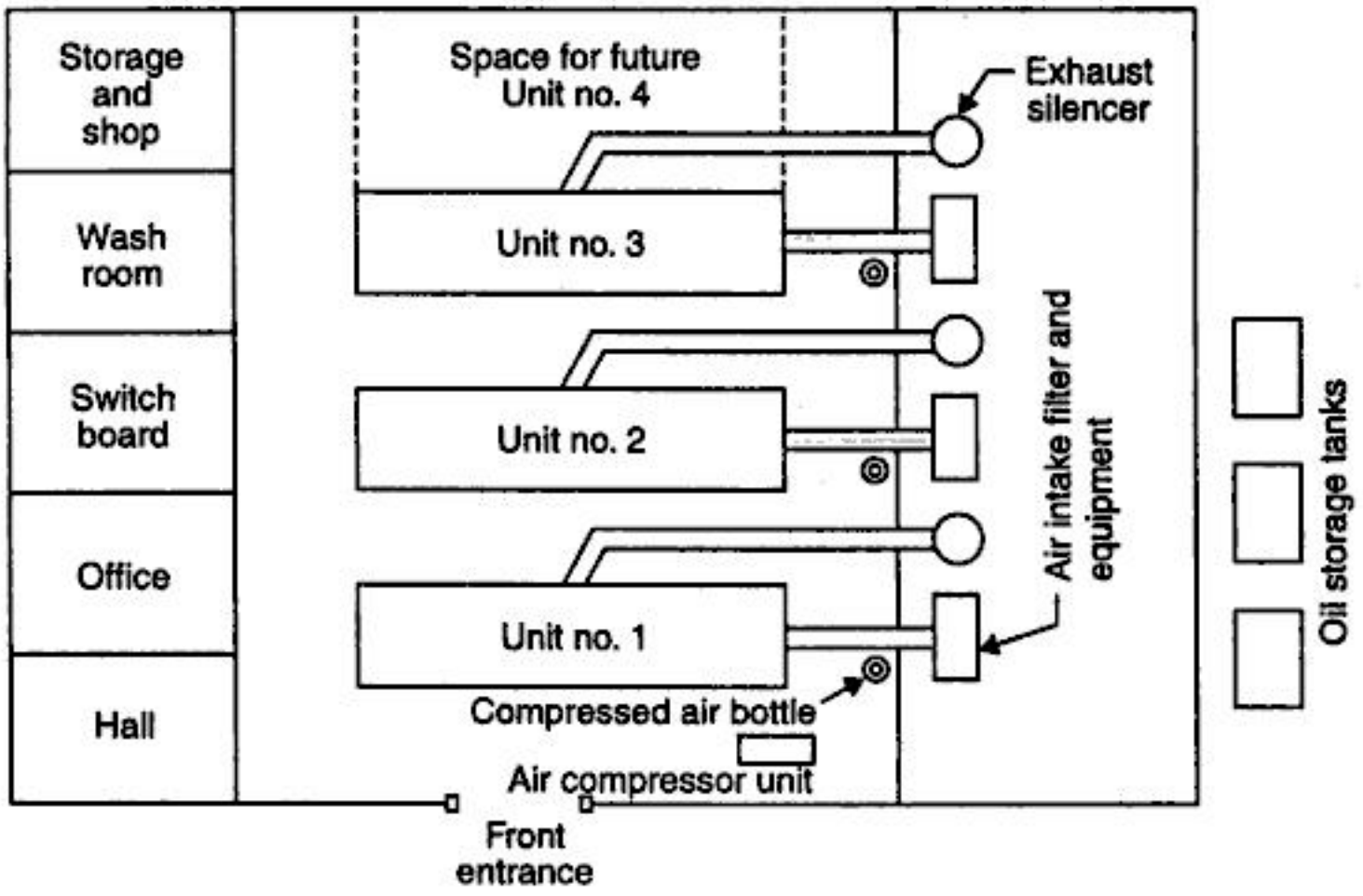

Fig. 3.5. Layout of a diesel engine power plant.

HIGHLIGHTS

1. Any type of engine or machine which derives heat energy from the combustion of fuel or any other source and converts this energy into mechanical work is termed as a *heat engine*.
2. Essential components of a diesel power plant are :
   (*i*) Engine (*ii*) Air intake system
   (*iii*) Exhaust system (*iv*) Fuel system
   (*v*) Cooling system (*vi*) Lubrication system
   (*vii*) Engine starting system (*viii*) Governing system.
3. Commonly used fuel injection system in a diesel power station :
   (*i*) Common-rail injection system
   (*ii*) Individual pump injection system
   (*iii*) Distribution system.
4. In liquid cooling following methods are used for circulating the water around the cylinder and cylinder head :
   (*i*) Thermo-system cooling (*ii*) Forced or pump cooling
   (*iii*) Cooling with thermostatic regulator (*iv*) Pressurised cooling
   (*v*) Evaporative cooling.
5. Various lubrication systems use for I.C. engines are :
   (*i*) Wet sump lubrication system
   (*ii*) Dry sump lubrication system
   (*iii*) Mist lubrication system.
6. The following three are the commonly used starting systems in large and medium size engines :
   (*i*) Starting by an auxiliary engine
   (*ii*) Use of electric motors or self starters
   (*iii*) Compressed air system.
7. The purpose of supercharging is to raise the volumetric efficiency above that value which can be obtained by normal aspiration.

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THEORETICAL QUESTIONS

1. What are the advantages and disadvantages of diesel power plants ?
2. State the applications of diesel power plant.
3. What factors should be considered while selecting a site for a diesel power plant ?
4. With the help of neat sketches give the construction and working of a four stroke diesel cycle engine.
5. List the essential components of a diesel power plant and explain them briefly.
6. Name and explain briefly various types of fuel injection systems.
7. Describe briefly the commonly used starting systems in large and medium size engines.
8. Discuss briefly the basic designs of C.I. engine combustion.
9. Give the types of diesel engines used for diesel power plants.
10. Give the layout of a diesel engine power plant.

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4

Gas Turbine Power Plants

4.1. Gas turbines—General aspects. 4.2. Applications of gas turbine plants. 4.3. Advantages and disadvantages of gas turbine power plants over diesel and thermal power plants. 4.4. Site selection. 4.5. The simple gas turbine plant. 4.6. Energy cycle for a simple-cycle gas turbine. 4.7. Performance terms. 4.8. Classification of gas turbine power plants. 4.9. Classification of gas turbines. 4.10. Combination gas turbine cycles—Combined turbine and steam power plants—Combined gas turbine and diesel power plants—Advantages of combined cycle. 4.11. Operation of a gas turbine. 4.12. Gas turbine power plant layout. 4.13. Components of a gas turbine power plant. 4.14. Various arrangements of gas turbine power plants. 4.15. Effect of thermodynamic variables on air rate. Highlights—Theoretical Questions.

4.1. GAS TURBINES—GENERAL ASPECTS

Probably a windmill was the first turbine to produce useful work, wherein there is no pre-compression and no combustion. The characteristic features of a gas turbine as we think of the name today include a *compression process* and a *heat-addition* (or combustion) process. The gas turbine represents perhaps the *most satisfactory way of producing very large quantities of power in a self-contained and compact unit*. The gas turbine may have an ample future use in conjunction with the oil engine. For smaller gas turbine units, the inefficiencies in compression and expansion processes become greater and to improve the thermal efficiency it is necessary to use a heat exchanger. In order that a small gas turbine may compete for economy with the small oil engine or petrol engine it is necessary that a compact effective heat exchanger be used in the gas turbine cycle. The thermal efficiency of the gas turbine alone is still quite modest 20 to 30% compared with that of a modern steam plant 38 to 40%. It is possible to construct *combined plants* whose efficiencies are of the order of 45% or more. Higher efficiencies might be attained in future.

The following are the major fields of application of gas turbines :

1. Aviation
2. Power generation
3. Oil and gas industry
4. Marine propulsion.

The efficiency of a gas turbine is not the criteria for the choice of this plant. A gas turbine is used in *aviation* and marine fields because *it is self contained, light weight not requiring cooling water and generally fit into the overall shape of the structure.* It is selected for '*power generation*' because of its *simplicity, lack of cooling water, needs quick installation and quick starting*. It is used in *oil and gas industry* because of *cheaper supply of fuel and low installation cost*.

The gas turbines have the following ***"limitations"*** **:**

1. They are not self starting.
2. Low efficiencies at part loads.

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3. Non-reversibility.
4. Higher rotor speeds.
5. Low overall plant efficiency.

In the last two decides, rapid progress has been observed in the *development and improvement of the gas turbine plants for electric power production*. The major progress has been observed in the following *directions* :

(*i*) Increase in unit capacities of gas turbine units.

(*ii*) Increase in their efficiency.

(*iii*) Drop in capital cost.

4.2. APPLICATIONS OF GAS TURBINE PLANTS

Gas turbine plants for the purpose of power plant engineering find the following *applications* :

1. To drive generators and supply peak loads in steam, diesel or hydroplants.
2. To work as combination plants with conventional steam boilers.
3. To supply mechanical drive for auxiliaries.

- These plants are well suited for *peak load service* since the fuel costs are somewhat higher and initial cost low. Moreover, *peak load operation permits use of water injection which increases turbine work by about 40% with an increase in heat rate of about 20%.* The short duration of increase in heat rate does not prove of any much harm.
- The combination arrangement of gas turbines with conventional boilers may be supercharging or for heat recovery from exhaust gases. In the *supercharging system* air is supplied to the boiler under pressure by a compressor mounted on the common shaft with turbine and gases formed as result of combination after coming out of the boiler pass through the gas turbine before passing through the economiser and the chimney.
- The application of the gas turbine to drive the auxiliaries is not strictly included under direct electric power generation by the turbines and would not be discussed.

4.3. ADVANTAGES AND DISADVANTAGES OF GAS TURBINE POWER PLANTS OVER DIESEL AND THERMAL POWER PLANTS

A. Advantages Over Diesel Plants :

1. The work developed per kg of air is large compared with diesel plant.
2. Less vibrations due to perfect balancing.
3. Less space requirements.
4. Capital cost considerably less.
5. Higher mechanical efficiency.
6. The running speed of the turbine (40,000 to 100,000 r.p.m.) is considerably large compared to diesel engine (1000 to 2000 r.p.m.).
7. Lower installation and maintenance costs.
8. The torque characteristics of turbine plants are far better than diesel plants.
9. The ignition and lubrication systems are simpler.
10. The specific fuel consumption does not increase with time in gas turbine plant as rapidly as in diesel plants.
11. Poor quality fuels can be used.

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Disadvantages :

1. Poor part load efficiency.
2. Special metals and alloys are required for different components of the plants.
3. Special cooling methods are required for cooling the turbine blades.
4. Short life.

B. Advantages Over Steam Power Plant :

1. No ash handling problem.
2. Low capital cost.
3. The gas turbine plants can be installed at selected load centre as space requirement is considerably less where steam plant cannot be accommodated.
4. Fewer auxiliaries required/used.
5. Gas turbines can be built relatively quicker. They require much less space and civil engineering works and water supply.
6. The gas turbine plant as peak load plant is more preferable as it can be brought on load quickly and surely.
7. The components and circuits of a gas turbine plant can be arranged to give the most economic results in any given circumstances which is not possible in case of steam power plants.
8. For the same pressure and initial temperature conditions the ratio of exhaust to inlet volume would be only 3.95 in case of gas turbine plant as against 250 for steam plant.
9. Above 550°C, the thermal efficiency of the gas turbine plant increases three times as fast the steam cycle efficiency for a given top temperature increase.
10. The site of the steam power plant is dictated by the availability of large cooling water whereas an open cycle gas turbine plant can be located near the load centre as no cooling water is required. The cooling water required for closed cycle gas turbine is hardly 10% of the steam power plant.
11. The gas turbine plants can work quite economically for short running hours.
12. Storage of fuel is much smaller and handling is easy.

4.4. SITE SELECTION

While selectinig the site for a gas turbine plant. The following *points* should be given due consideration :

1. The plant should be located near the load centre to avoid transmission costs and losses.
2. The site should be away from business centres due to noisy operations.
3. Cheap and good quality fuel should be easily available.
4. Availability of labour.
5. Availability of means of transportation.
6. The land should be available at a cheap price.
7. The bearing capacity of the land should be high.

4.5. THE SIMPLE GAS TURBINE PLANT

A gas turbine plant may be defined as one "*in which the principal primemover is of the turbine type and the working medium is a permanent gas*".

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Refer Fig. 4.1. A simple gas turbine plant consists of the following :

1. *Turbine.*
2. *A compressor* mounted on the same shaft or coupled to the turbine.
3. *The combustor.*
4. *Auxiliaries* such as starting device, auxiliary lubrication pump, fuel system, oil system and the duct system etc.

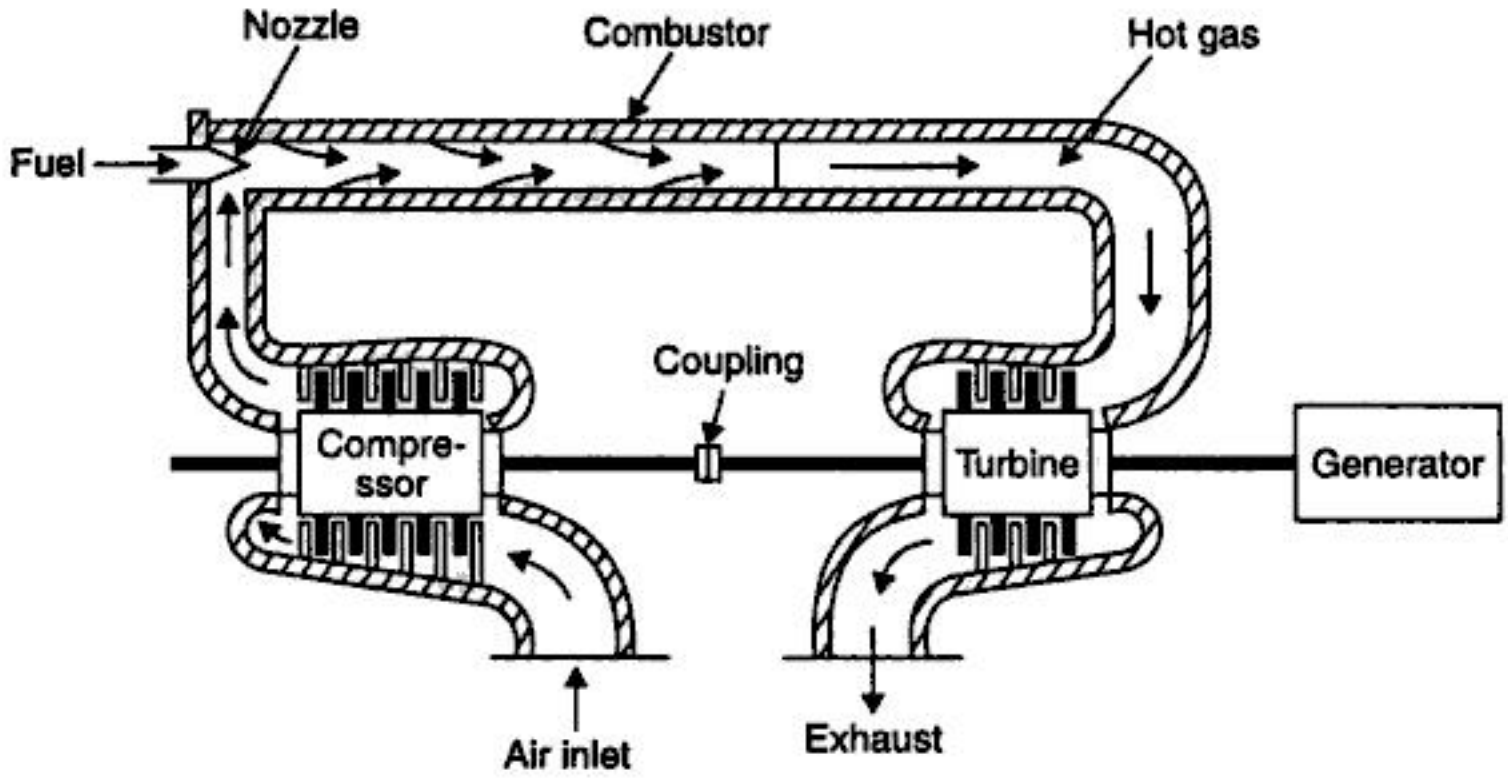

Fig. 4.1. Arrangement of a simple gas turbine plant.

A modified plant may have in addition to above an *intercooler, a regenerator, a reheater* etc.

The working fluid is compressed in a compressor which is generally rotary, multistage type. Heat energy is added to the compressed fluid in the chamber. This high energy fluid, at high temperature and presssure, then expands in the turbine unit thereby generating power. Part of the power generated is consumed in driving the generating compressor and accessories and the rest is utilised in electrical energy. The gas turbines work on open cycle, semi-closed cycle or closed cycle. In order to improve efficiency, compression and expansion of working fluid is carried out in multistages.

4.6. ENERGY CYCLE FOR A SIMPLE-CYCLE GAS TURBINE

Fig. 4.2 shows an energy-flow diagram for a simple-cycle gas turbine, the description of which is as follows :

- The air brings in minute amount of energy (measured above 0°C).
- Compressor adds considerable amount of energy.
- Fuel carries major input to cycle.
- Sum of fuel and compressed-air energy leaves combustor to enter turbine.
- In turbine smallest part of entering energy goes to useful output, largest part leaves in exhaust.

Shaft energy to drive compressor is about twice as much as the useful shaft output.

Actually the shaft energy keeps circulating in the cycle as long as the turbine runs. The important comparison is *the size of the output with the fuel input*. For the simple-cycle gas turbine the output may run about 20 per cent of the fuel input for pressure and temperature conditions at turbine inlet. This means 80% of the fuel energy is wasted. While the 20% thermal efficiency is not too bad, it can be improved by including *additional heat recovery apparatus.*

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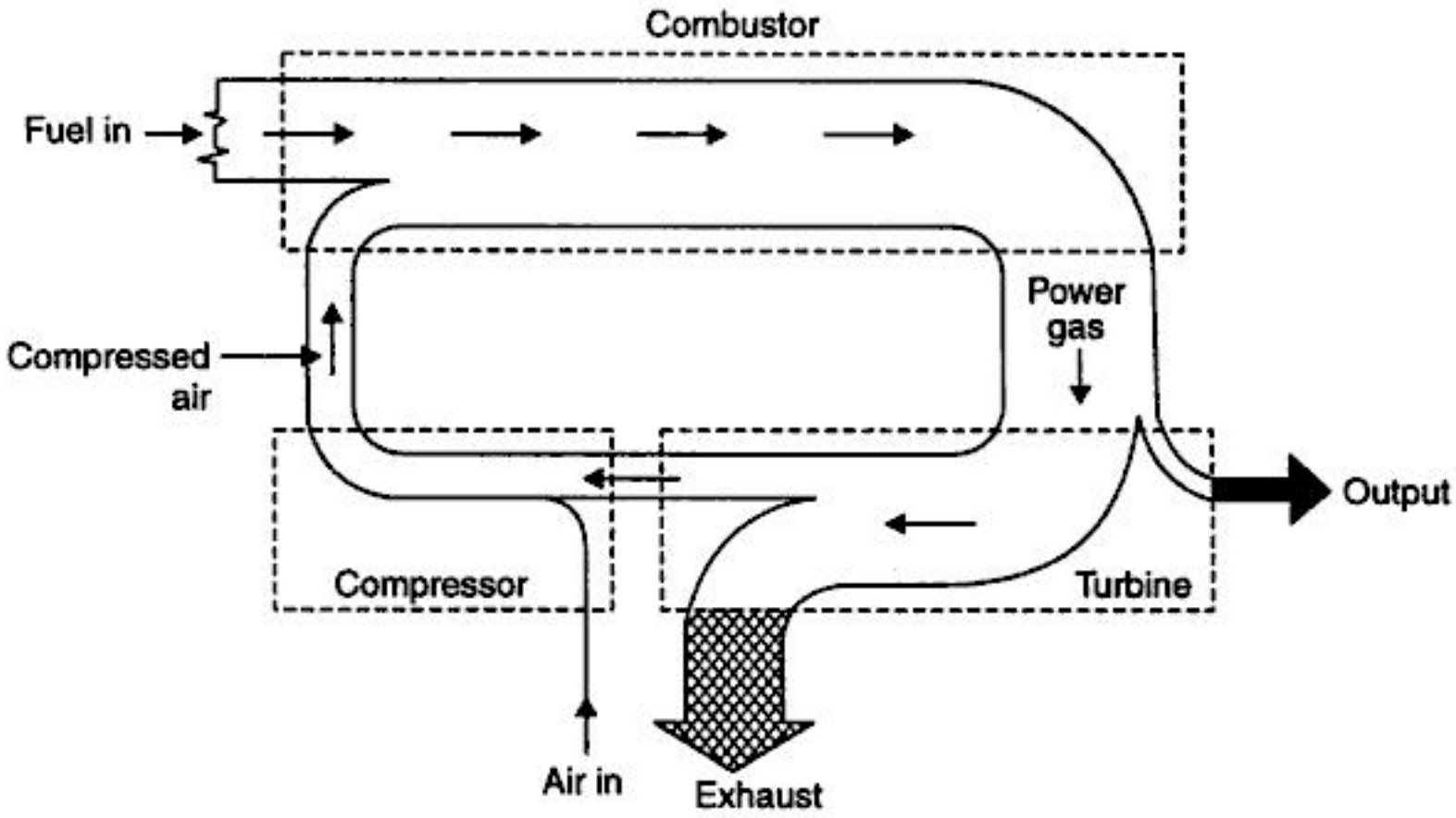

Fig. 4.2. Energy flow diagram for gas-turbine unit.

4.7. PERFORMANCE TERMS

Some of the important terms used to measure performance of a gas turbine are defined as follows :

1. Pressure ratio. It is the ratio of cycle's highest to its lowest pressure, usually highest-pressure-compressor discharges to the lowest-pressure-compressor inlet pressures.

2. Work ratio. It is the ratio of network output to the total work developed in the turbine or turbines.

3. Air ratio. Kg of air entering the compressor inlet per unit of cycle net output, for example, kg/kWh.

4. Compression efficiency. It is the ratio of work needed for ideal air compression through a given pressure range to work actually used by the compressor.

5. Engine efficiency. It is the ratio of the work actually developed by the turbine expanding hot power gas through a given pressure range to that would be yielded for ideal expansion conditions.

6. Machine efficiency. It is the collective term meaning both engine efficiency and compressor efficiency of turbine and compressor, respectively.

7. Combustion efficiency. It is the ratio of heat actually released by 1 kg of fuel to heat that would be released by complete perfect combustion.

8. Thermal efficiency. It is the percentage of total energy input appearing as net work output of the cycle.

4.8. CLASSIFICATION OF GAS TURBINE POWER PLANTS

The gas turbine power plants may be *classified* according to the following criteria :

1. By application :

(*i*) *In aircraft*

(*a*) Jet propulsion (*b*) Prop-jets

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(*ii*) *Stationary*

(*a*) Peak load unit (*b*) Standby unit

(*c*) End of transmission line unit (*d*) Base load unit

(*e*) Industrial unit.

(*iii*) Locomotive

(*iv*) Marine

(*v*) Transport.

2. By cycle :

(*i*) Open cycle (*ii*) Closed cycle

(*iii*) Semi-closed cycle.

3. According to arrangement :

(*i*) Simple (*ii*) Single shaft

(*iii*) Multi-shaft (*iv*) Intercooled

(*v*) Reheat (*vi*) Regenerative

(*vii*) Combination.

4. According to combustion :

(*i*) Continuous combustion (*ii*) Intermittent combustion.

5. By fuel :

(*i*) Solid fuel (*ii*) Liquid fuel

(*iii*) Gaseous fuel.

4.9. CLASSIFICATION OF GAS TURBINES

The gas turbines are mainly divided into two groups :

1. **Constant pressure combustion gas turbine**

(*a*) Open cycle constant pressure gas turbine

(*b*) Closed cycle constant pressure gas turbine.

2. **Constant volume combustion gas turbine**

In almost *all the fields open cycle gas turbine plants are used. Closed cycle plants were introduced at one stage because of their ability to burn cheap fuel.* In between their progress remained slow because of availability of cheap oil and natural gas. Because of rising oil prices, now again, the attention is being paid to closed cycle plants.

4.10. COMBINATION GAS TURBINE CYCLES

4.10.1. Combined Turbine and Steam Power Plants

The characteristics of the gas turbine plants render these plants very well suited for use in combination with steam or hydro-plants. These plants can be quickly started for emergency or peak load service. The combination *'gas-turbine-steam cycles' aim at utilising the heat of exhaust gases from the gas turbine and thus, improve the overall plant efficiency.*

Three popular designs of combination cycle comprise of :

1. Heating feed water with exhaust gases.

2. Employing the gases from a supercharged boiler to expand in the gas turbine.

3. Employing the gases as combustion air in the steam boiler.

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the gases are expanded in the gas turbine, its exhaust being used to heat feed water before being discharged through the stack. The *heat transfer rate in this boiler is very high as compared to that in a conventional boiler due to higher pressure of gases ; and a smaller size of steam generator is needed* for the same steam raising capacity as of the conventional plant. Further more, since the gases in the furnace are already under pressure, *no induced draught or forced draught fans are needed* and there is saving in power consumption which would otherwise be spent in mechanical draught supply. Through this combination an *overall improvement in heat rate is to the extent of above 7 percent.*

3. Employing the gases as combustion air in the steam boiler :

Refer Fig. 4.5. When exhaust gases are used as preheated air for combustion in the boiler, an improvement of about 5 percent in overall heat rate of the plant results. The boiler is fed with supplementary fuel and air, and is made larger than the conventional furnace. If only the turbine exhaust is used in the furnace without any supplementary fuel firing, the arrangement becomes a waste heat boiler.

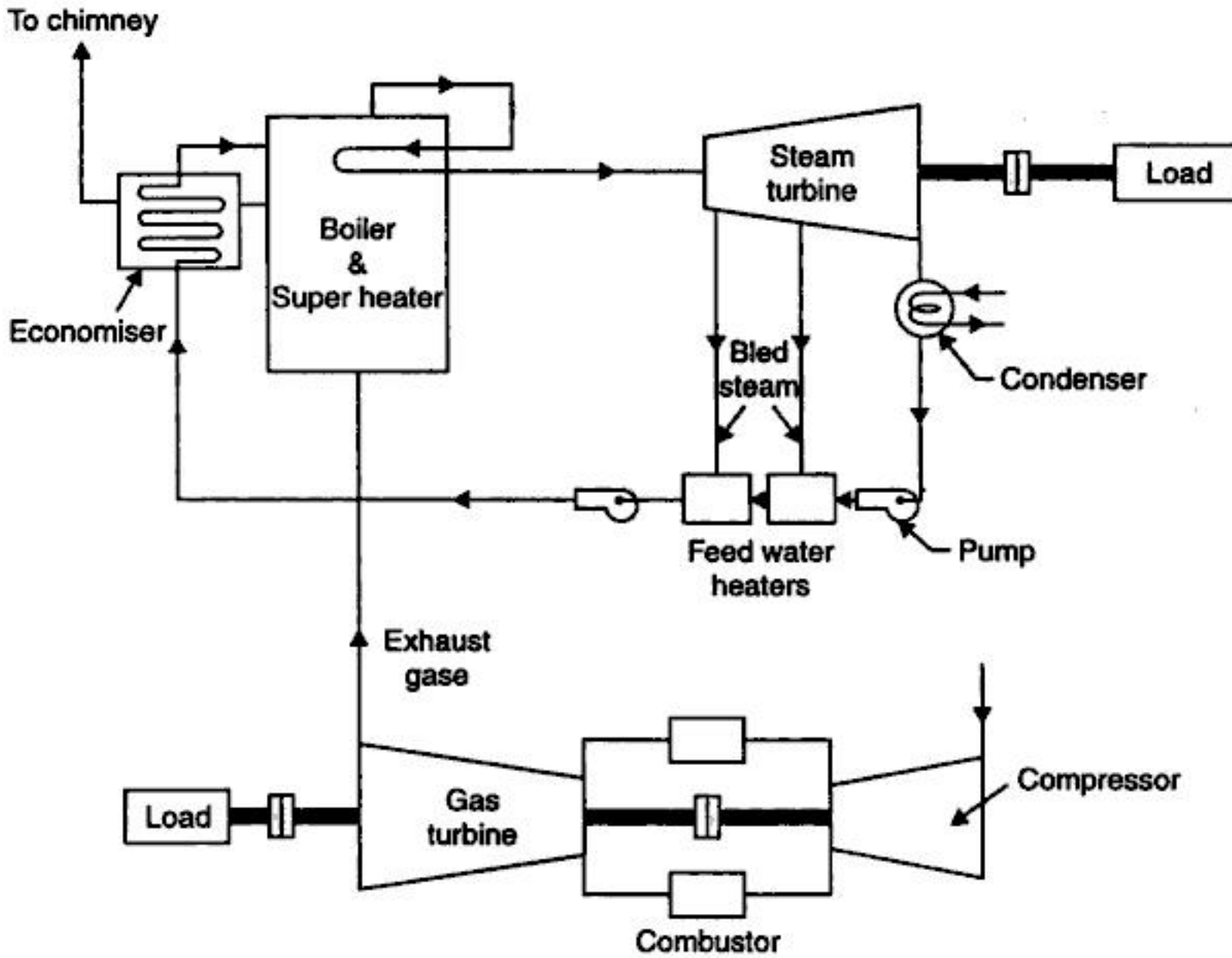

Fig. 4.5. Use of exhaust gases for combustion in the furnance of the steam plant.

- Fig. 4.6 shows the gain in heat rate due to combination cycle.
- Fig. 4.7 shows the comparison of a steam and closed cycle gas plant.

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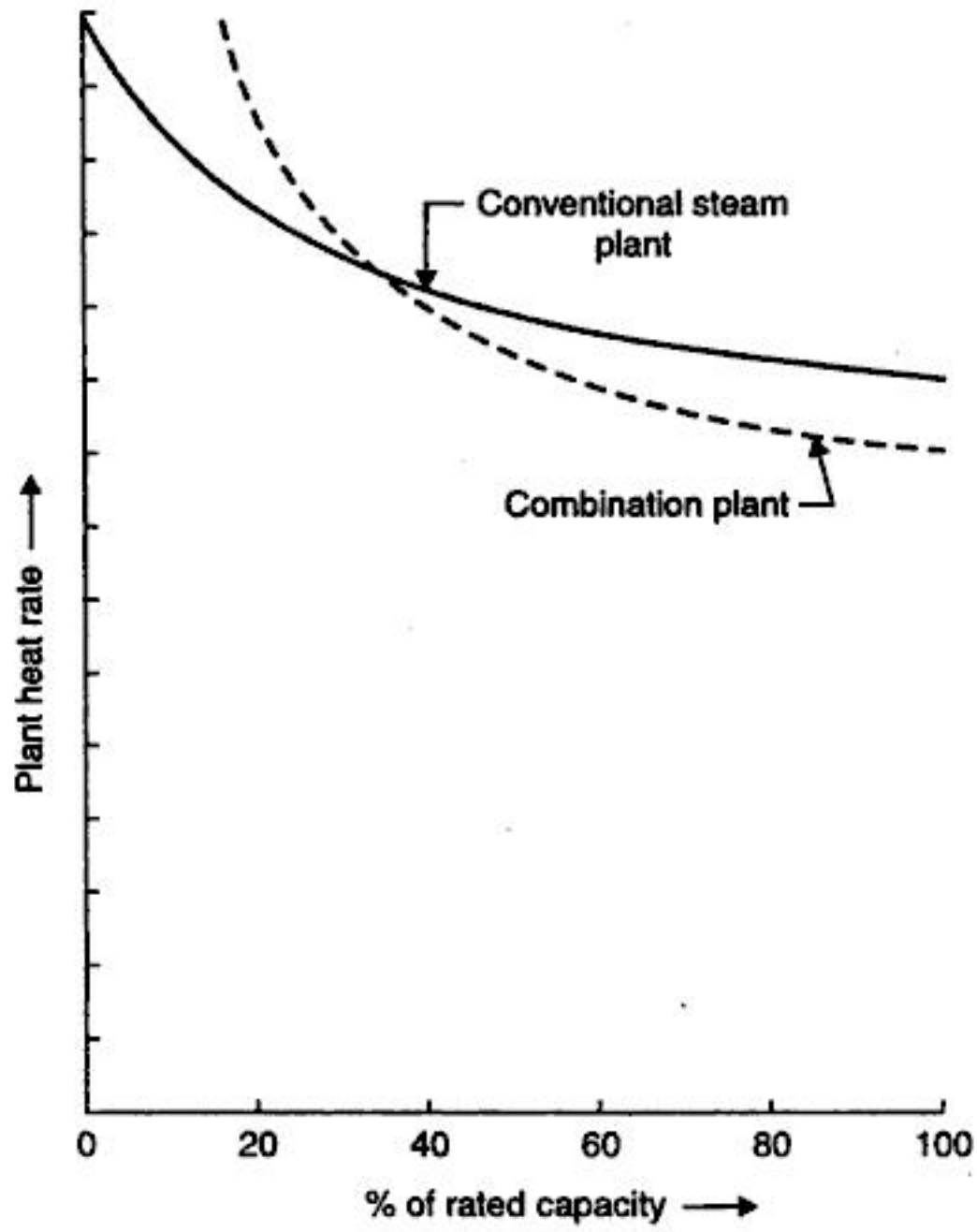

Fig. 4.6

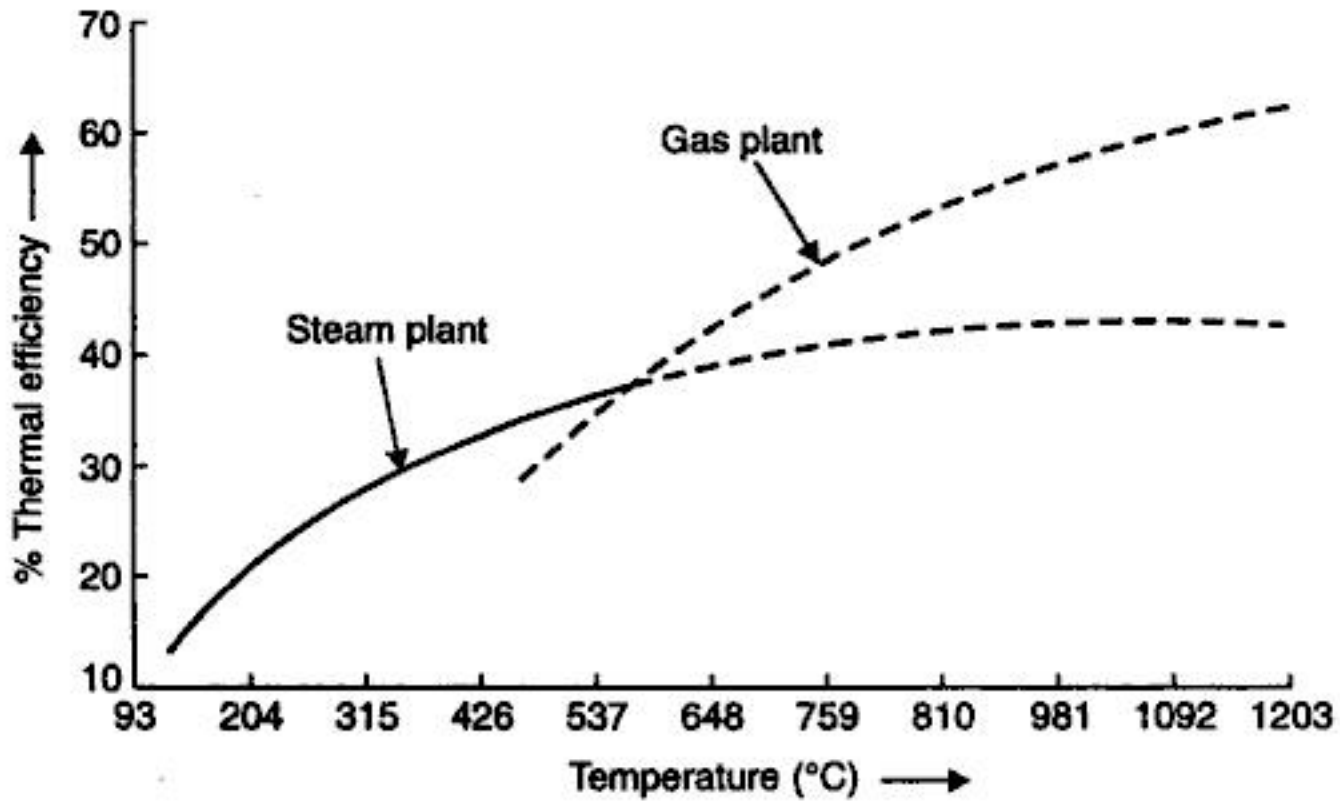

Fig. 4.7. Comparison between steam and closed cycle gas turbine plant.

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4.10.2. Combined Gas Turbine and Diesel Power Plants

The performance of a diesel engine can be improved by combining it with an exhaust driven gas turbine. It can be achieved by the following three combinations :

1. Turbo-charging.
2. Gas-generator.
3. Compound engine.

1. Turbo-charging :

Refer Fig. 4.8. This method is known as *supercharging*. Here the exhaust of the diesel engine is expanded in the gas turbine and the work output of the gas turbine is utilised to run a compressor which supplies the pressurised air to the diesel engine to increase its output. The load is coupled to the diesel engine shaft and the output of the gas turbine is just sufficient to run the compressor.

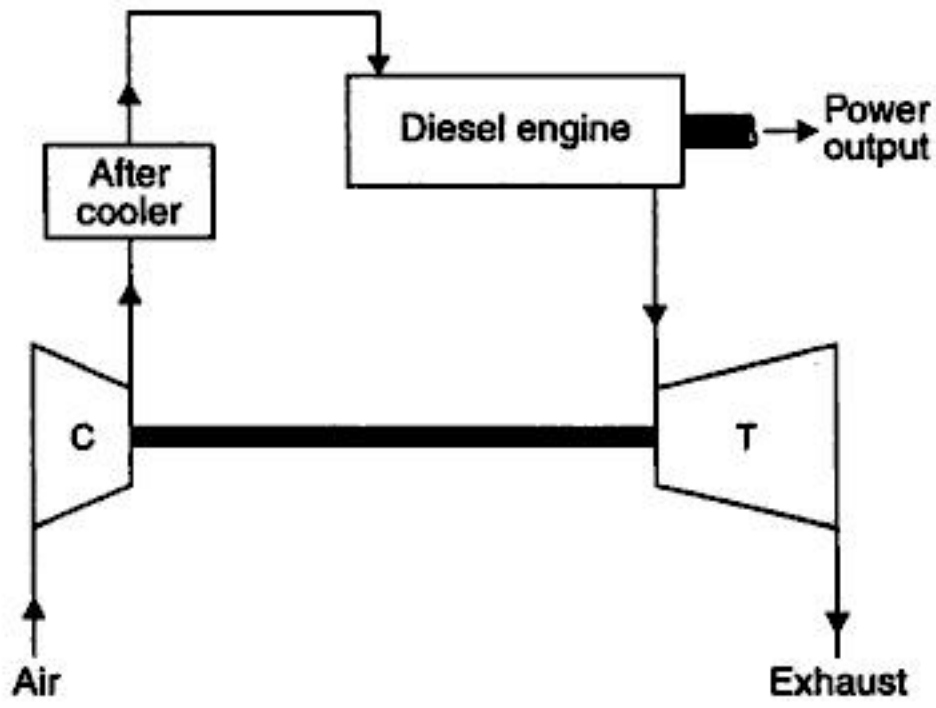

Fig. 4.8. Turbo-charging.

2. Gas-generator :

Fig. 4.9 shows the schematic arrangement. Here the compressor which supplies the compressed air to the diesel engine is not driven from gas turbine but from the diesel engine through some suitable drive. The output of the diesel engine is consumed in driving the air compressor and the gas turbine supplies the power.

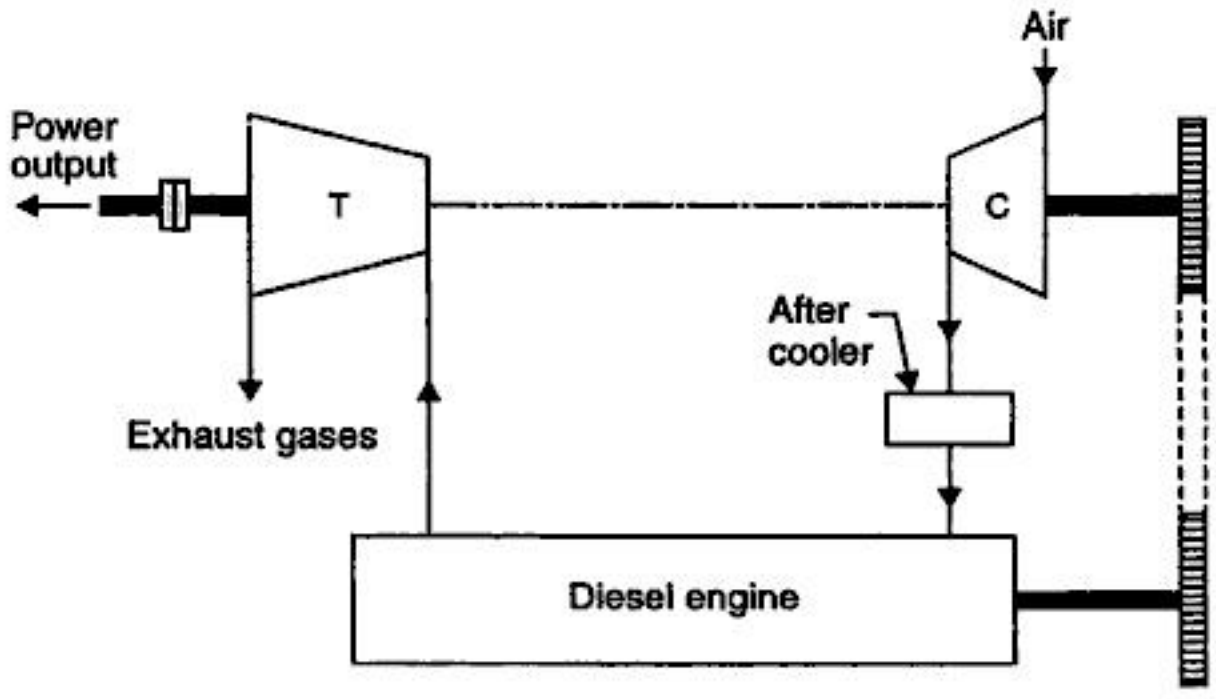

Fig. 4.9. Gas-generator.

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- Whereas the major portion of the total space is occupied by the intercoolers, combustion chambers, heat exchangers, waste heat boilers and interconnecting duct work, the rotating parts of the plant form a very small part of the total volume of the plant.

4.13. COMPONENTS OF A GAS TURBINE POWER PLANT

The main components of a gas turbine power plant are enumerated and discussed as follows :

1. Gas turbines
2. Compressors
3. Combustor
4. Intercoolers and regenerators.

1. Gas turbines :

A turbine basically employs vanes or blades mounted on a shaft and enclosed in a casing. The flow of fluid through the turbine in *most design is axial and tangential to the rotor* at a nearly constant or increasing radius. The basic requirements of the turbines are : (*i*) *Light weight* (*ii*) *High efficiency* (*iii*) *Reliability in operation and* (*iv*) *Long working life.* Large work output can be obtained per stage with high blade speeds when the blades are designed to sustain higher stresses. *More stages of the turbine are always preferred in gas turbine power plant because it helps to reduce the stresses in the blades and increases the overall life of the turbine.*

It is essential to cool the gas turbine blades for long life as these are continuously subjected to high temperature gases. The blades can be cooled by different methods, the common method being the *air-cooling*. The air is passed through the holes provided through the blade.

The following **accessories** are fitted to the turbine :

(*i*) *Tachometer.* It shows the speed of the machine and also actuates the fuel regulator in case the speed shoots above or falls below the regulated speed, so that the fuel regulator admits less or more fuel into the combustor and varies the turbine power according to the demand. The tachometer is driven through a gear box.

(*ii*) *An overspeed governor.* The governor backs off fuel feed if exhaust temperature from the turbine exceeds the safe limit, thermal switches at the turbine exhaust acting on fuel control to maintain present maximum temperature.

(*iii*) *Lubricating oil pump.* It supplies oil to the bearings under pressure.

(*iv*) Starting motor or engine

(*v*) Starting set-up gear

(*vi*) Oil coolers

(*vii*) Filters

(*viii*) Inlet and exhaust mufflers.

2. Compressors :

The compressors which are commonly used are of the following two types :

1. Centrifugal type.
2. Axial flow type.

- The *'centrifugal compressor'* consists of an *impeller* and a *diffuser*. The *impeller imparts the high kinetic energy to the air* and *diffuser converts the kinetic energy into the pressure energy.* The pressure ratio of 2 to 3 is possible with single stage compressor and it can be increased upto 20 with 3-stage compressor. The compressors may have single or double inlet. The *single inlet* compressors are designed to handle

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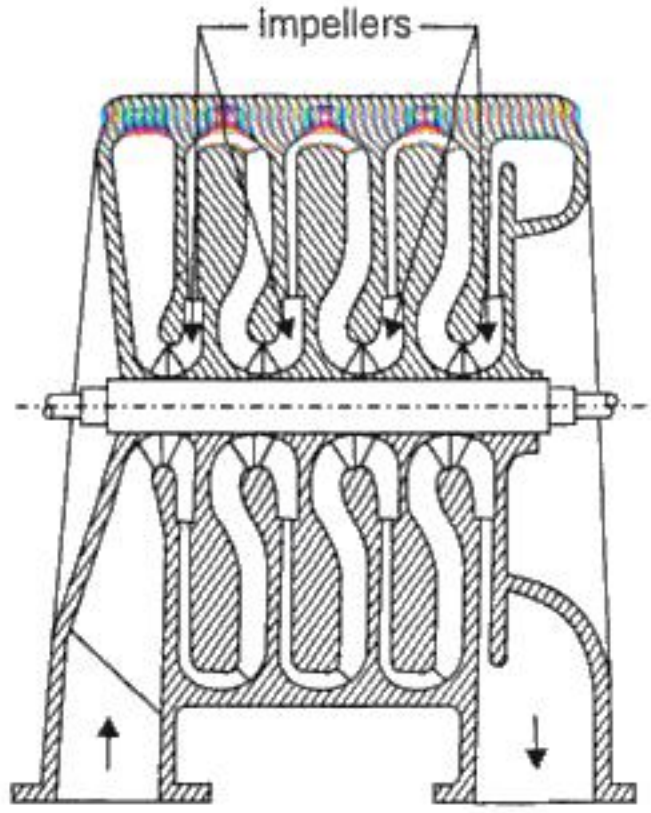

Fig. 4.13. Multi-stage single flow axial compressor.

An axial compressor is capable of *delivering constant volumes of air over varying discharge pressures*. These machines are well suited for large capacities at moderate pressures. If the impeller of a centrifugal compressor is designed to give an axial component of velocity at the exit, the design becomes a *mixed flow type*.

3. Combustor :

The primary function of the *combustor is to provide for the chemical reaction of the fuel and air being supplied by the compressor*. It must fulfil the following *conditions* :

(*i*) Combustion must take place at high efficiency because of the effect of the combustion efficiency on the thermal efficiency of the gas turbine cycle.

(*ii*) The pressure losses must be low.

(*iii*) Ignition must be reliable and accomplished with ease over a wide range of atmospheric condition especially in aircraft installation.

(*iv*) Thorough mixing of fuel and air.

(*v*) Carbon deposits must not be formed under any conditions.

The physical process of combustion may be divided into four important steps :

1. Formation of reactive mixture
2. Ignition
3. Flame propagation
4. Cooling of combustion products with air. Atomisation should be done for perfect burning.

Fig. 4.14 shows an arrangement of a typical combustor design which employs an *outer cylindrical shell* with a *conical inner sleeve* which is provided with ports or slots along the length. At the cone apex is fitted a *nozzle* through which fuel is sprayed in a conical pattern into the sleeve and near this is an *igniting device* or spark plug. A fuel line conveys the fuel to the nozzle. A few air ports provided close to the situation of the nozzle supply the combustion air directly to the fuel and are fitted with vanes to produce a whirling motion of oil and thereby create turbulence. The rest of the air admitted ahead of combustion zone serves to cool the combustor and outlet gases. The combustor is best located between the compressor outlet and turbine inlet and takes the shape of a cylinder. Alternatively, the 'can' arrangement may be used in which the flow is divided to pass through a number of smaller cylindrical chambers. In this latter design the adjacent chambers may be

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interconnected through small tubes so that a simple igniting device fitted in one of the chambers serves all the chambers.

The *nozzle* sprays the fuel under pressure in an atomised conical spray. The fuel is delivered to the nozzle through the fuel line and flows out through tangential slots in the nozzle, thus being given a whirling motion in an annular chamber from where it passes out through a small orifice in the conical pattern of desired angle.

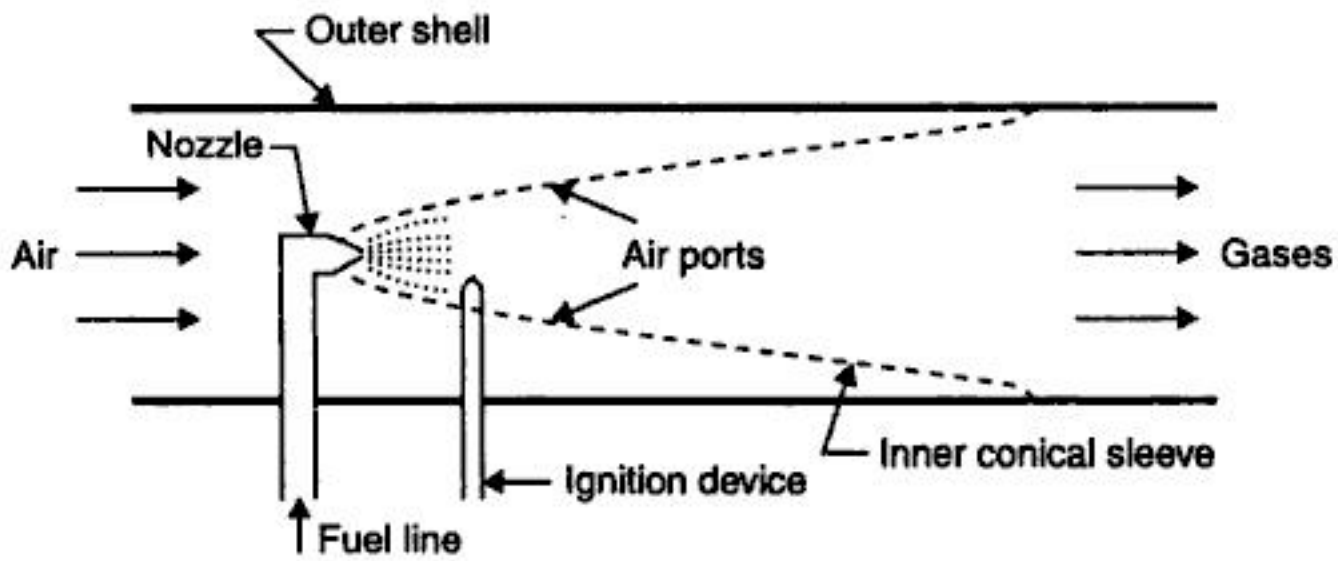

Fig. 4.14. Arrangement of a combustor.

4. Intercoolers and regenerators :

Intercoolers. In a gas turbine plant the *intercooler* is generally used when the pressure ratio used is sufficiently large and the compression is completed with two or more stages. The cooling of compressed air is generally done with the use of cooling water. A *cross-flow* type intercooler (Fig. 4.15) is generally preferred for effective heat transfer.

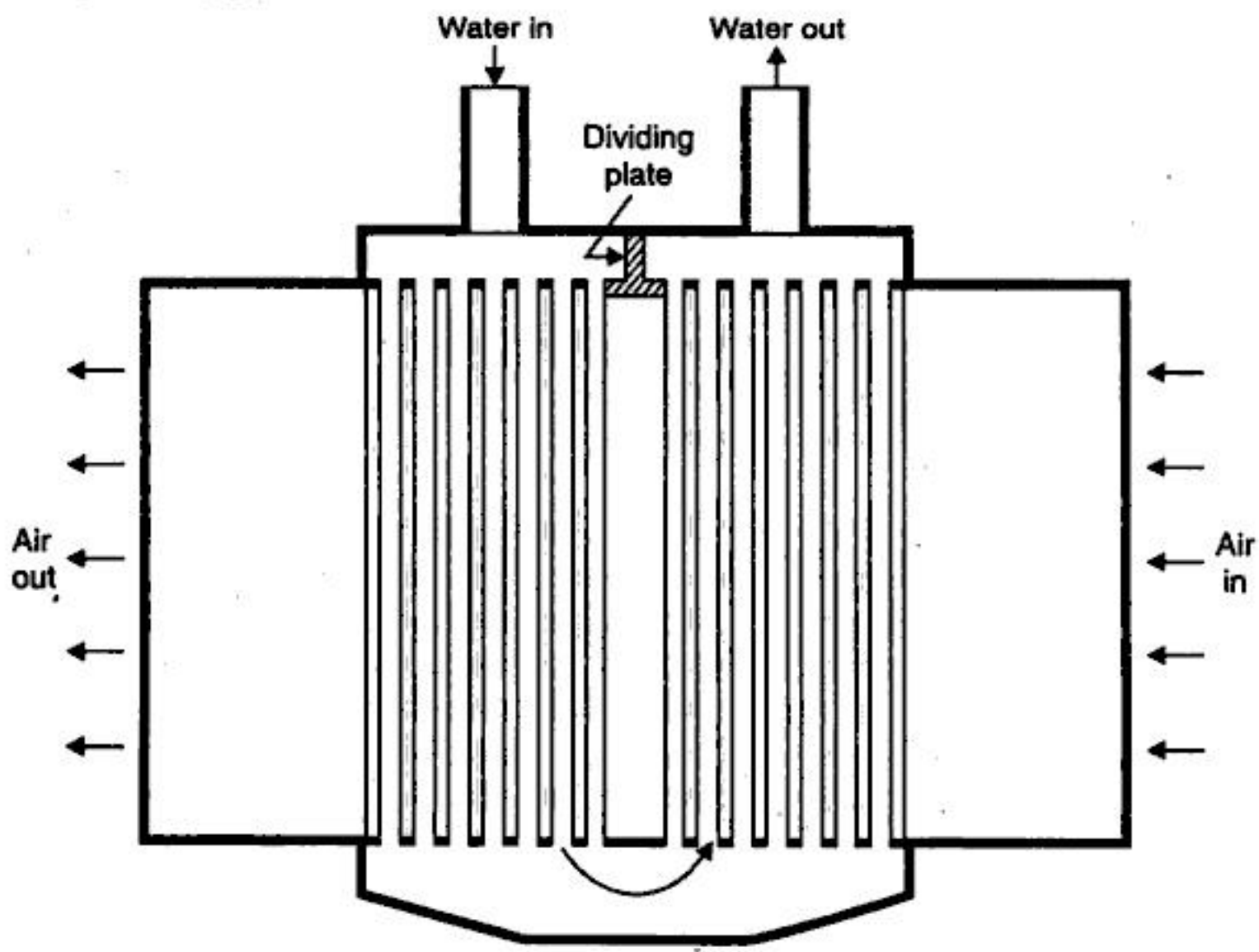

Fig. 4.15. Intercooler.

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Regenerators. Refer to Fig. 4.16. In the regenerator heat transfer takes place between the exhaust gases and cool air. It is usually made in shell and tube construction with gas flowing inside the tubes and air outside the tubes, the two fluids being made to flow in opposite directions. Since the gas is bound to carry dust and deposit the same on the heat transfer surface, the internal flow through the tubes is convenient as the tube inside can be easily cleaned with brushes whereas it is very difficult to clean the outside surface of tubes. The effect of counterflow is the highest average temperature difference between the heating and heated medium with consequent high heat transfer between the two fluids. A number of baffles in the air put in the shell make the air to flow in contact with maximum heat transfer. However, *the pressure drop in both air and gas during the flow should be minimum possible.*

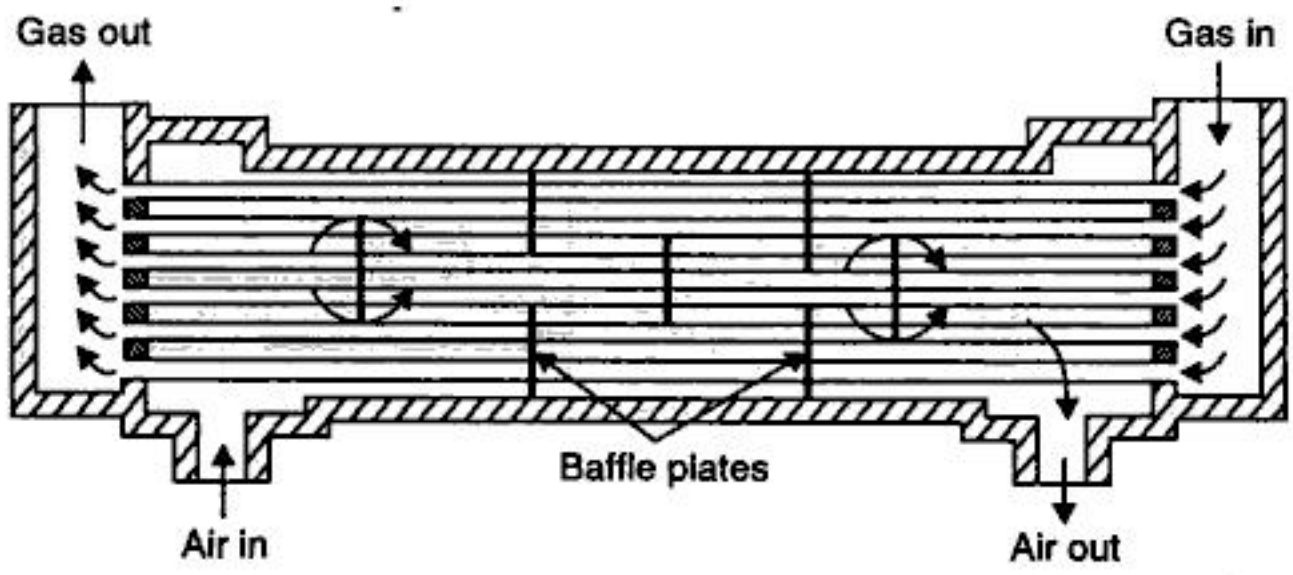

Fig. 4.16. Regenerator.

4.14. VARIOUS ARRANGEMENTS OF GAS TURBINE POWER PLANTS

The various arrangements of gas turbine plants are shown in Figs. 4.17 to 4.22.

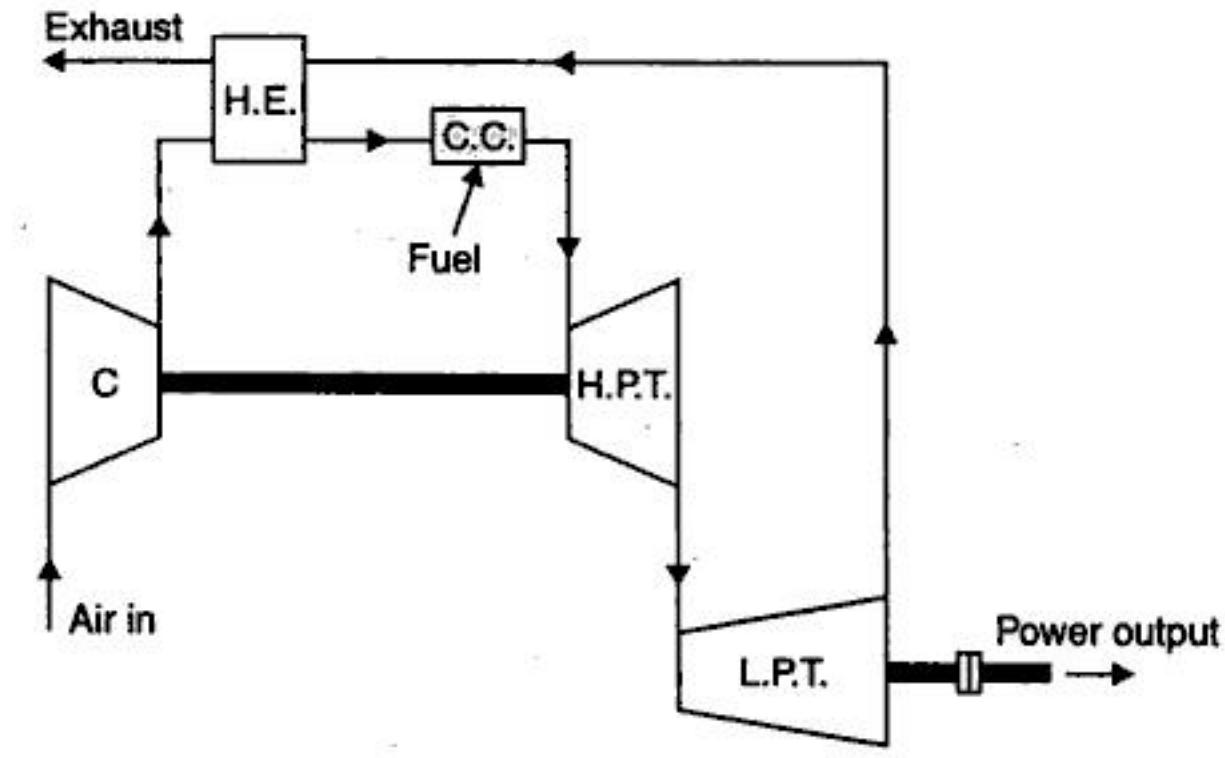

Fig. 4.17. Open cycle gas turbine with separate power turbine.

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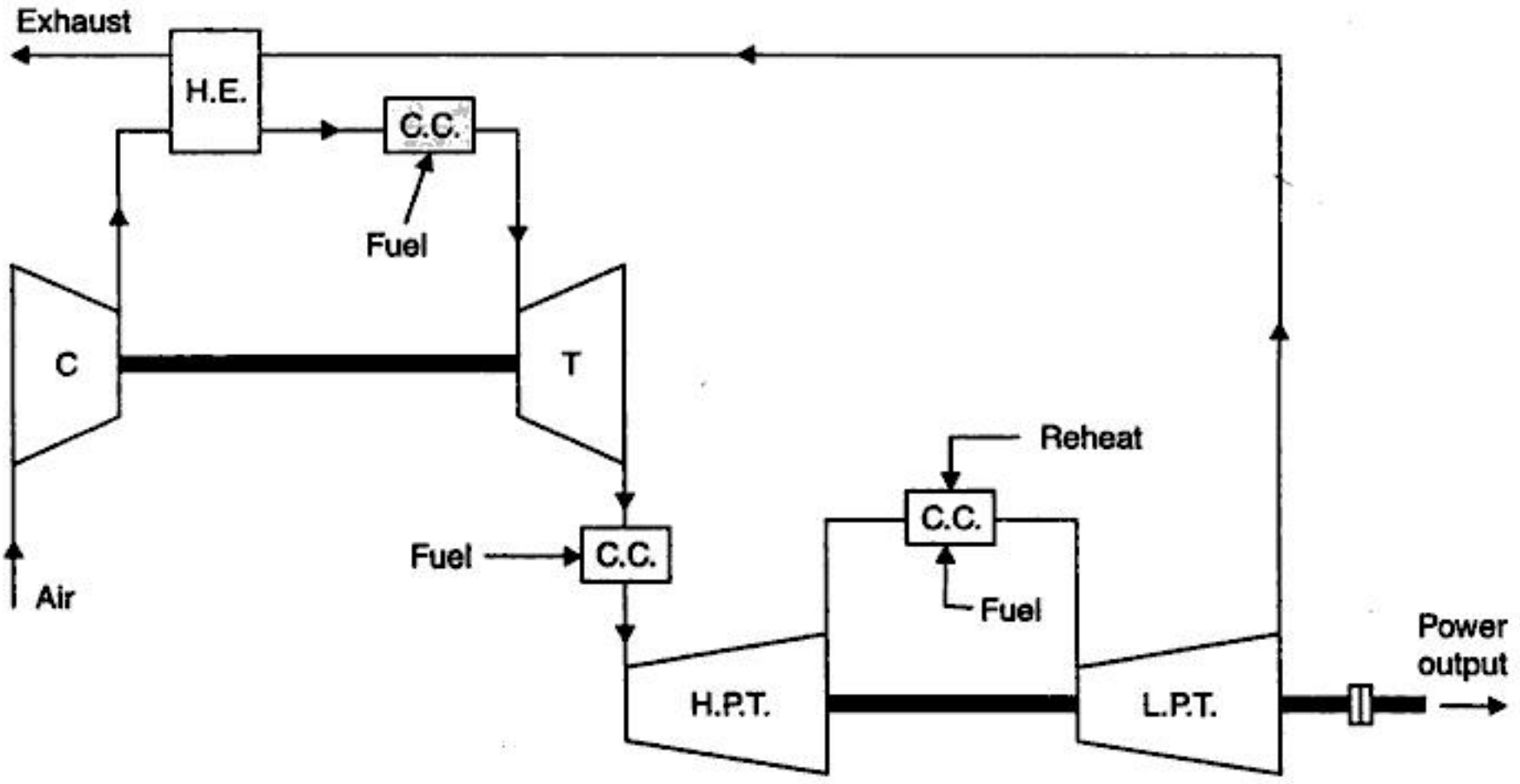

Fig. 4.18. Series flow gas turbine plant.

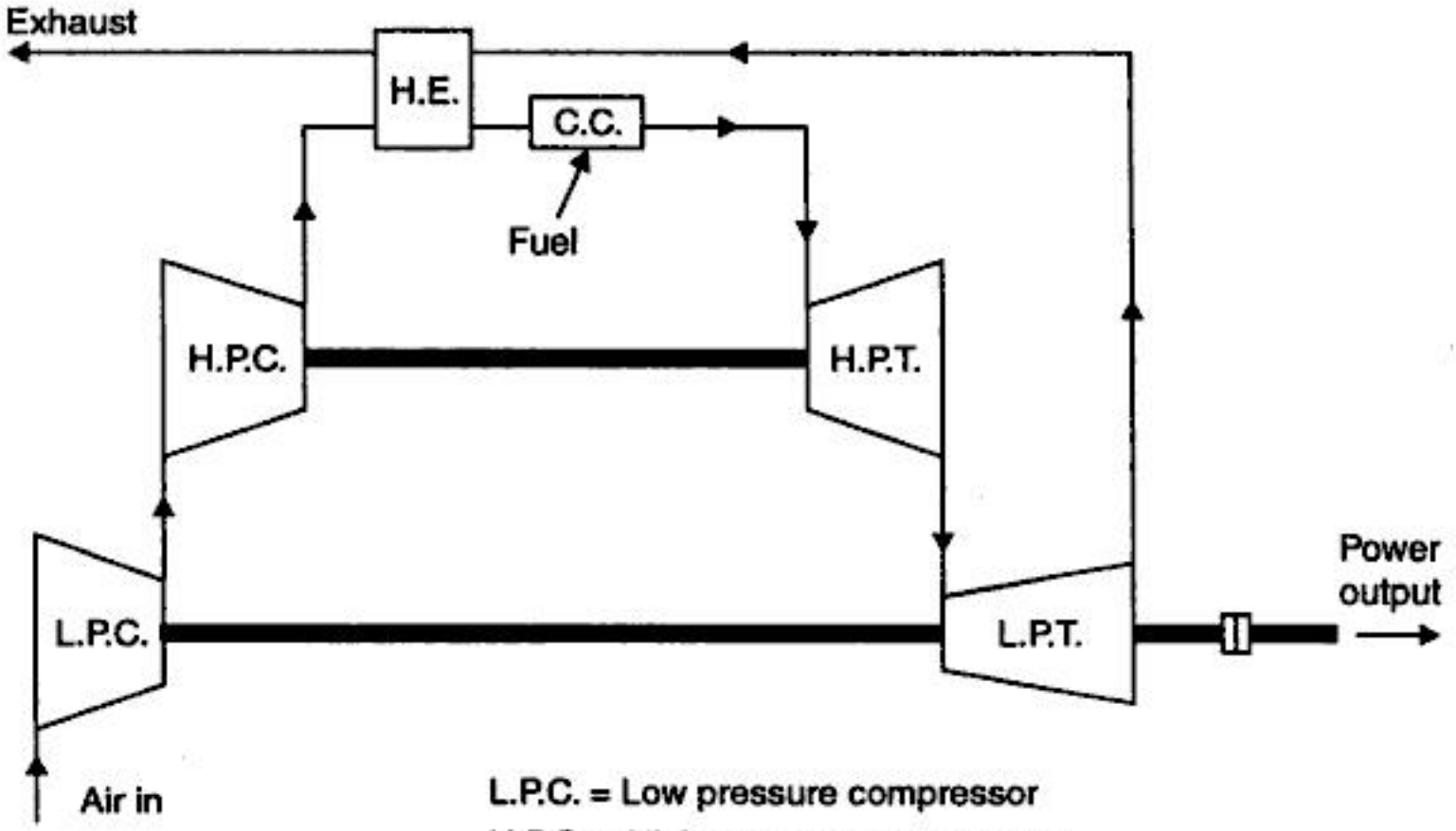

Fig. 4.19. Parallel flow gas turbine plant.

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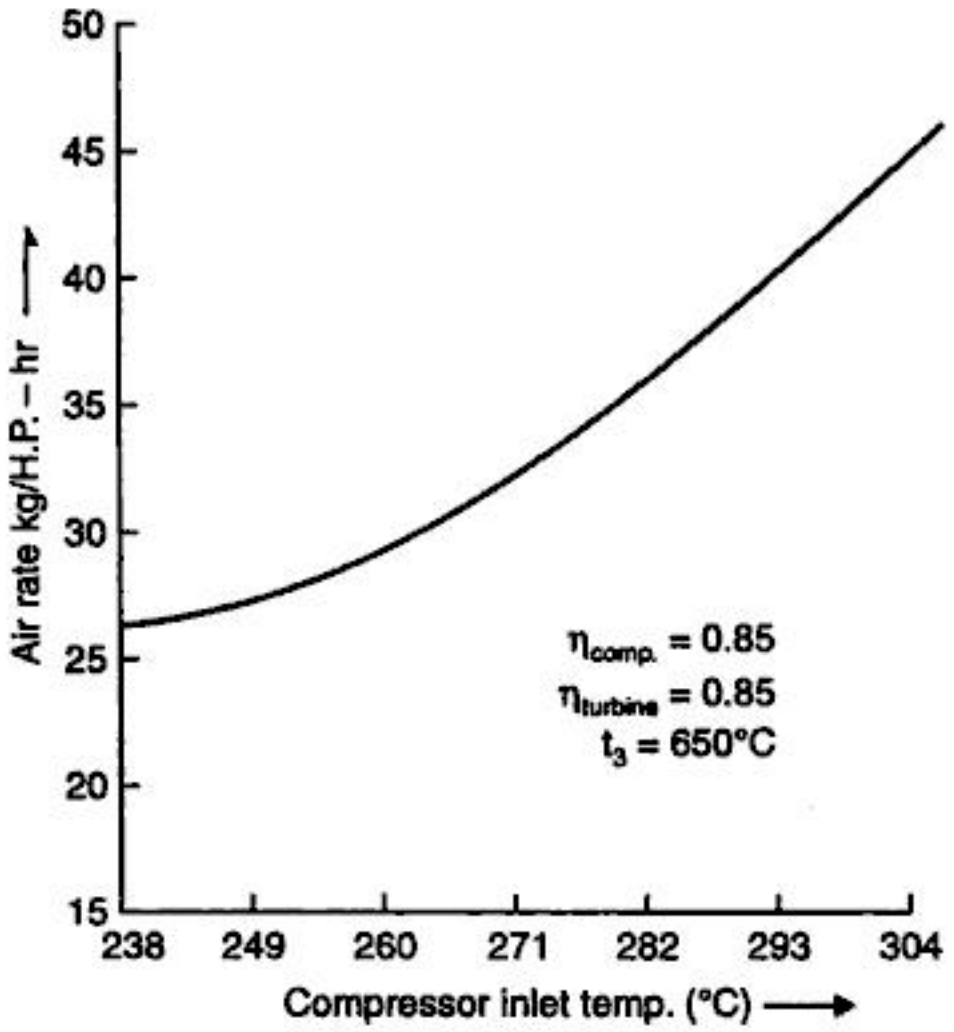

Fig. 4.24. Effect of the compressor inlet temperature on air rate.

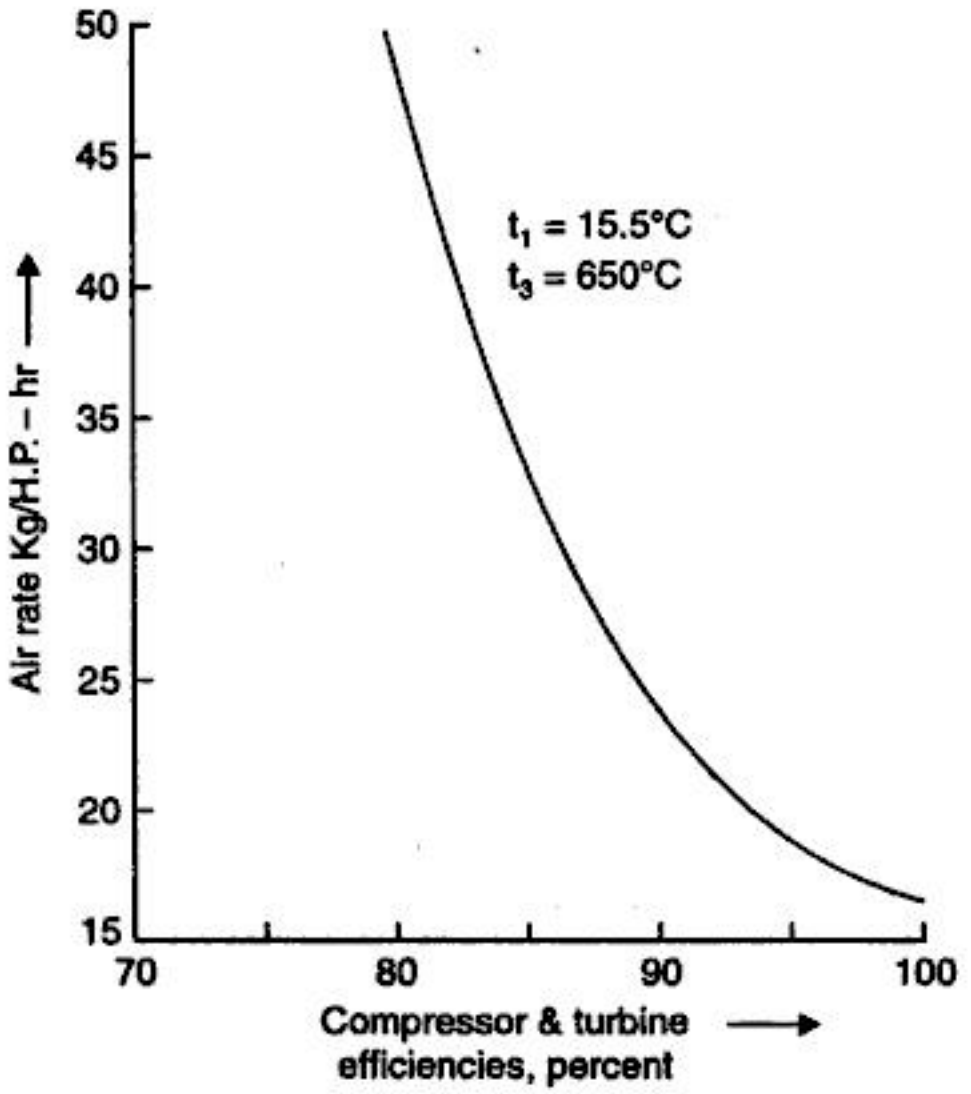

Fig. 4.25. Effect of compressor and turbine efficiencies on air rate.

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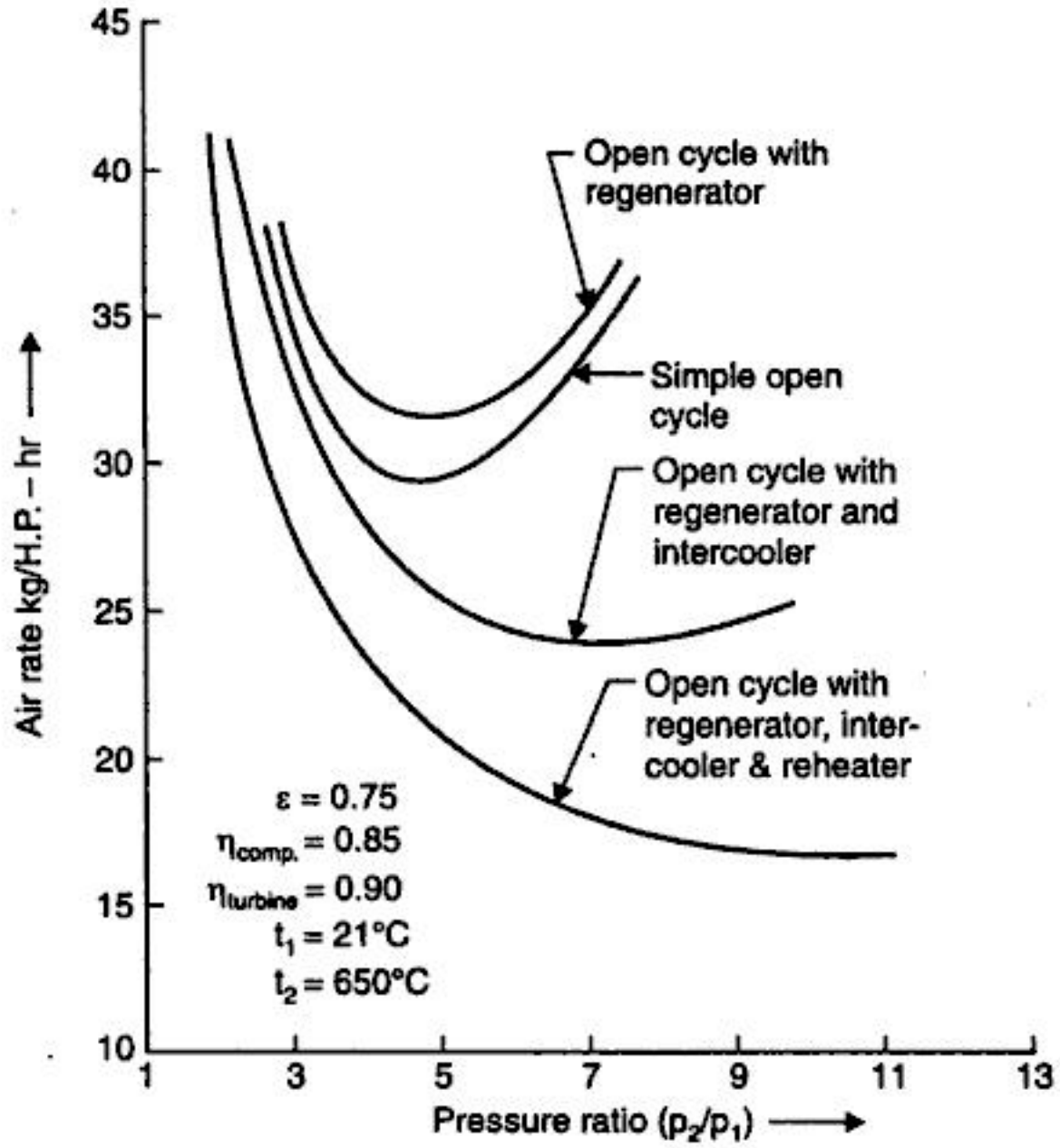

Fig. 4.26. Effect of thermal refinements on air rate.

HIGHLIGHTS

1. The major fields of application of gas turbines are :
   (*i*) Aviation (*ii*) Power generation
   (*iii*) Oil and gas industry (*iv*) Marine propulsion.
2. A gas turbine plant may be defined as one "in which the principal prime-mover is of the turbine type and the working medium is a permanent gas".
3. A simple gas turbine plant consists of the following :
   (*i*) Turbine (*ii*) Compressor
   (*iii*) Combustor (*iv*) Auxiliaries.
   A modified plant may have in addition an *intercooler, a regenerator, a reheater etc.*
4. Methods for improvement of thermal efficiency of open cycle gas turbine plant are :
   (*i*) Intercooling (*ii*) Reheating (*iii*) Regeneration.
5. *Free-piston engine plants* are the conventional gas turbine plants with the difference that the air compressor and combustion chamber are replaced by a free piston engine.

THEORETICAL QUESTIONS

1. What are the major fields of application of gas turbine ?
2. State the limitations of gas turbines.

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3. List the applications of gas turbine plants.
4. State the advantages and disadvantages of gas turbine power plants over diesel and thermal power plants.
5. What factors should be considered while selecting a site for a gas turbine power plant ?
6. Give the description of a simple gas turbine plant.
7. Explain with the help of a neat diagram the energy cycle for a simple-cycle gas turbine.
8. Define the following performance terms :

   Air ratio, Pressure ratio, Work ratio, Compressor efficiency, Engine efficiency, Machine efficiency, Combustion efficiency and Thermal efficiency.
9. How are gas turbine power plants classified ?
10. How are gas turbines classified ?
11. What do you mean by "combination gas turbine cycles". Explain briefly combined gas turbine and steam power plants.
12. List the advantages of 'combined cycle'.
13. How is a gas turbine 'started' and 'shut down' ?
14. Explain with a neat sketch the layout of a gas turbine power plant.
15. Enumerate and explain briefly the components of a gas turbine power plant.

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5

Hydro-Electric Power Plant

5.1. Introduction. 5.2. Application of hydro-electric plants. 5.3. Advantages and disadvantages of hydro-electric plants. 5.4. Selection of site for a hydro-electric plant. 5.5. Essential features/elements of hydro-electric power plant—Catchment area—Reservoir—Dam—Spillways—Conduits—Surge tanks—Primemovers—Draft tubes—Power house and equipment. 5.6. Classification of hydro-electric power plants—High head power plants—Medium head power plants—Low head power plants—Base load plants—Peak load plants—Run-of-river plants without pondage—Run-of-river plant with pondage—Storage type plants—Pumped storage plants—Mini and microhydel plants. 5.7. Hydraulic turbines—Classification of hydraulic turbines— Description of various types of turbines—Specific speed of a turbine—Efficiencies of a turbine—Cavitation—Performance of hydraulic turbines—Governing of hydraulic turbines—Selection of turbines. 5.8. Plant layout. 5.9. Hydro-plant auxiliaries. 5.10. Cost of hydro-plant. 5.11. Average life of hydro-plant components. 5.12. Hydro-plant controls. 5.13. Electrical and mechanical equipment in a hydro-plant. 5.14. Combined hydro and steam power plants. 5.15. Comparison of hydro-power stations with thermal power stations. 5.16. Underground hydro-plants. 5.17. Automatic and remote control of hydro-station. 5.18. Safety measures in hydro-electric power plants. 5.19. Preventive maintenance of hydro-plant. 5.20. Calculation of available hydro-power. 5.21. Cost of hydro-power. 5.22. Hydrology—Introduction—The hydrologic cycle—Measurement of run-off—Hydrograph—Flow duration curve—Mass curve. 5.23. Hydro-power development in India. Highlights—Theoretical Questions—Unsolved Examples.

5.1. INTRODUCTION

- In hydro-electric plants energy of water is utilised to move the turbines which in turn run the electric generators. The energy of water utilised for power generation may be kinetic or potential. The *kinetic energy* of water is its energy in motion and is a function of mass and velocity, while the *potential energy* is a function of the difference in level/head of water between two points. In either case continuous availability of a water is a basic necessity ; to ensure this, water collected in natural lakes and reservoirs at high altitudes may be utilised or water may be artificially stored by constructing dams across flowing streams. The ideal site is one in which a good system of natural lakes with substantial catchment area, exists at a high altitude. *Rainfall is the primary source of water* and depends upon such factors as temperature, humidity, cloudiness, wind etc. The usefulness of rainfall for power purposes further depends upon several complex factors which include its intensity, time distribution, topography of land etc. However it has been observed that only a small part of the rainfall can actually be utilised for power generation. A significant part is accounted for by *direct evaporation*, while another similar quantity *seeps* into the soil and forms the underground storage. Some water is also absorbed by

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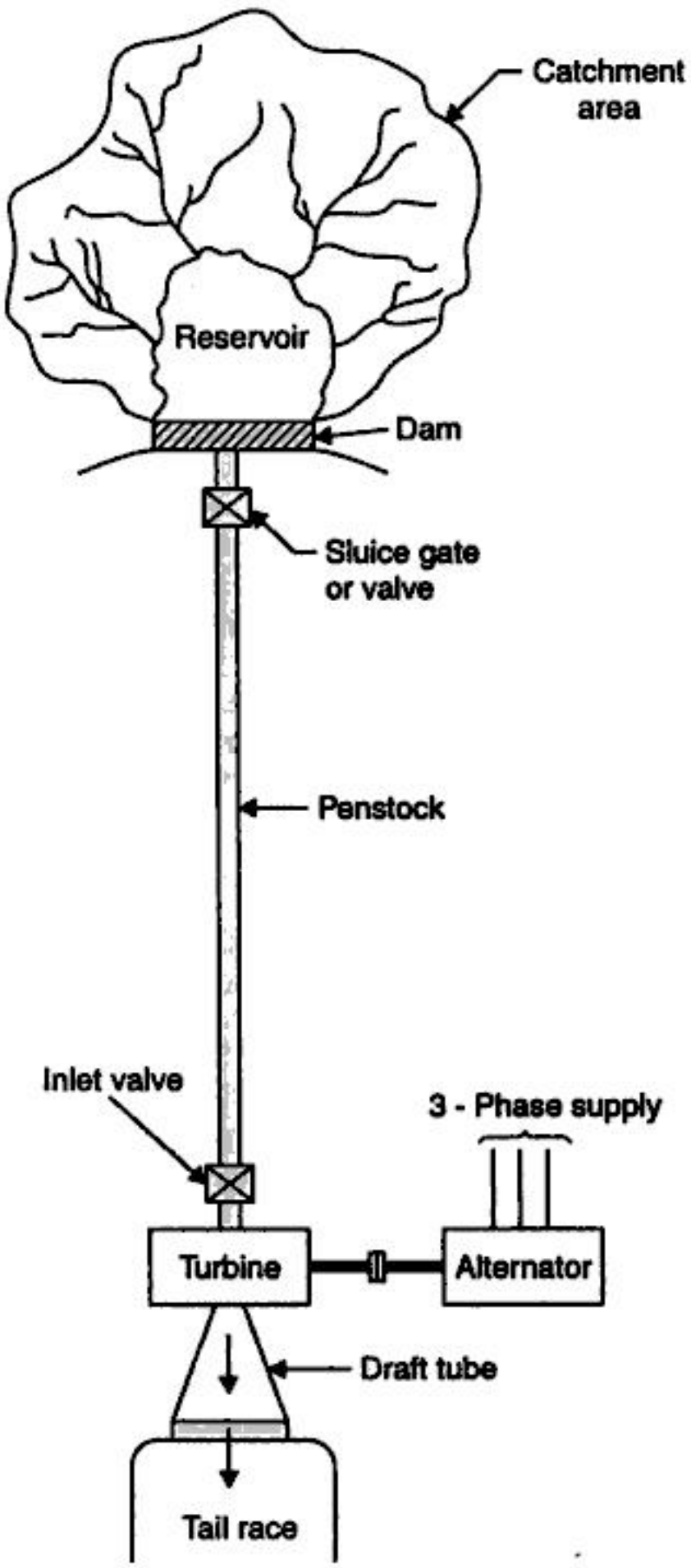

Fig. 5.1. Flow sheet of hydro-electric power plant.

5.6. CLASSIFICATION OF HYDRO-ELECTRIC POWER PLANTS

Hydro-electric power stations may be *classified* as follows :

A. According to availability of head :

1. High head power plants
2. Medium head power plants
3. Low head power plants.

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B. According to the nature of load :

1. Base load plants
2. Peak load plants.

C. According to the quantity of water available :

1. Run-of-river plant without pondage
2. Run-of-river plant with pondage
3. Storage type plants
4. Pump storage plants
5. Mini and micro-hydel plants

A. According to availability of head :

The following figures give a rough idea of the heads under which the various types of plants work :

(*i*) High head power plants	100 m and above
(*ii*) Medium head power plants	30 to 100 m
(*iii*) Low head power plants	25 to 80 m.

Note. It may be noted that figures given above overlap each other. Therefore it is difficult to classify the plants directly on the basis of head alone. The basis, therefore, technically adopted is the *specific speed* of the turbine used for a particular plant.

5.6.1. High Head Power Plants

These types of plants work under heads ranging from 100 to 2000 metres. Water is usually stored up in lakes on high mountains during the rainy season or during the season when the snow melts. The rate of flow should be such that water can last throughout the year.

Fig. 5.2 shows high head power plant layout. Surplus water discharged by the spillway cannot endanger the stability of the main dam by erosion because they are separated. The tunnel through the mountain has a surge chamber excavated near the exit. Flow is controlled by head gates at the tunnel intake, butterfly valves at the top of the penstocks, and gate valves at the turbines. This type of site might also be suitable for an underground station.

The *Pelton wheel* is the common primemover used in high *head power plants*.

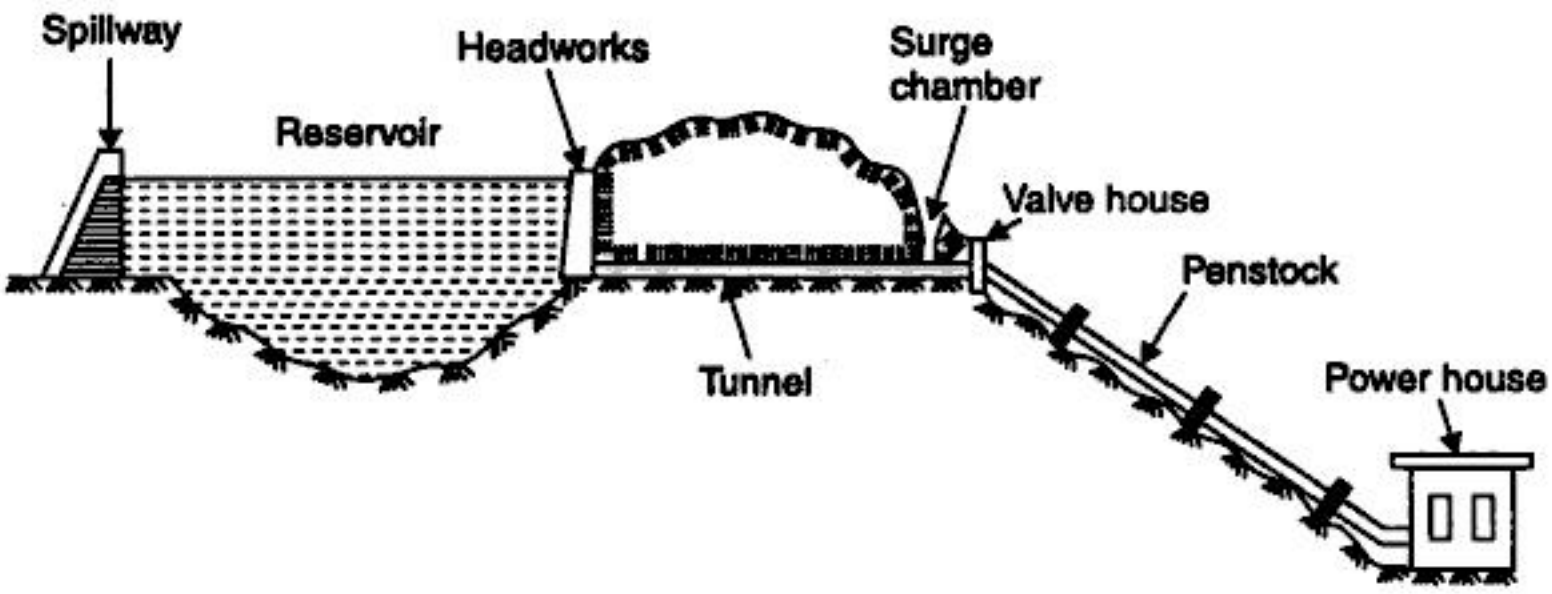

Fig. 5.2. High head power plant layout. The main dam, spillway, and powerhouse stand at widely separated locations. Water flows from the reservoir through a tunnel and penstocks to the turbines.

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5.6.2. Medium Head Power Plants

Refer Fig. 5.3. When the operating head of water lies between 30 to 100 metres, the power plant is known as medium head power plant. This type of plant commonly uses *Francis turbines*. The forebay provided at the beginning of the penstock serves as water reservoir. In such plants, the water is generally carried in open canals from main reservoir to the forebay and then to the power-house through the penstock. The forebay itself works as a surge tank in this plant.

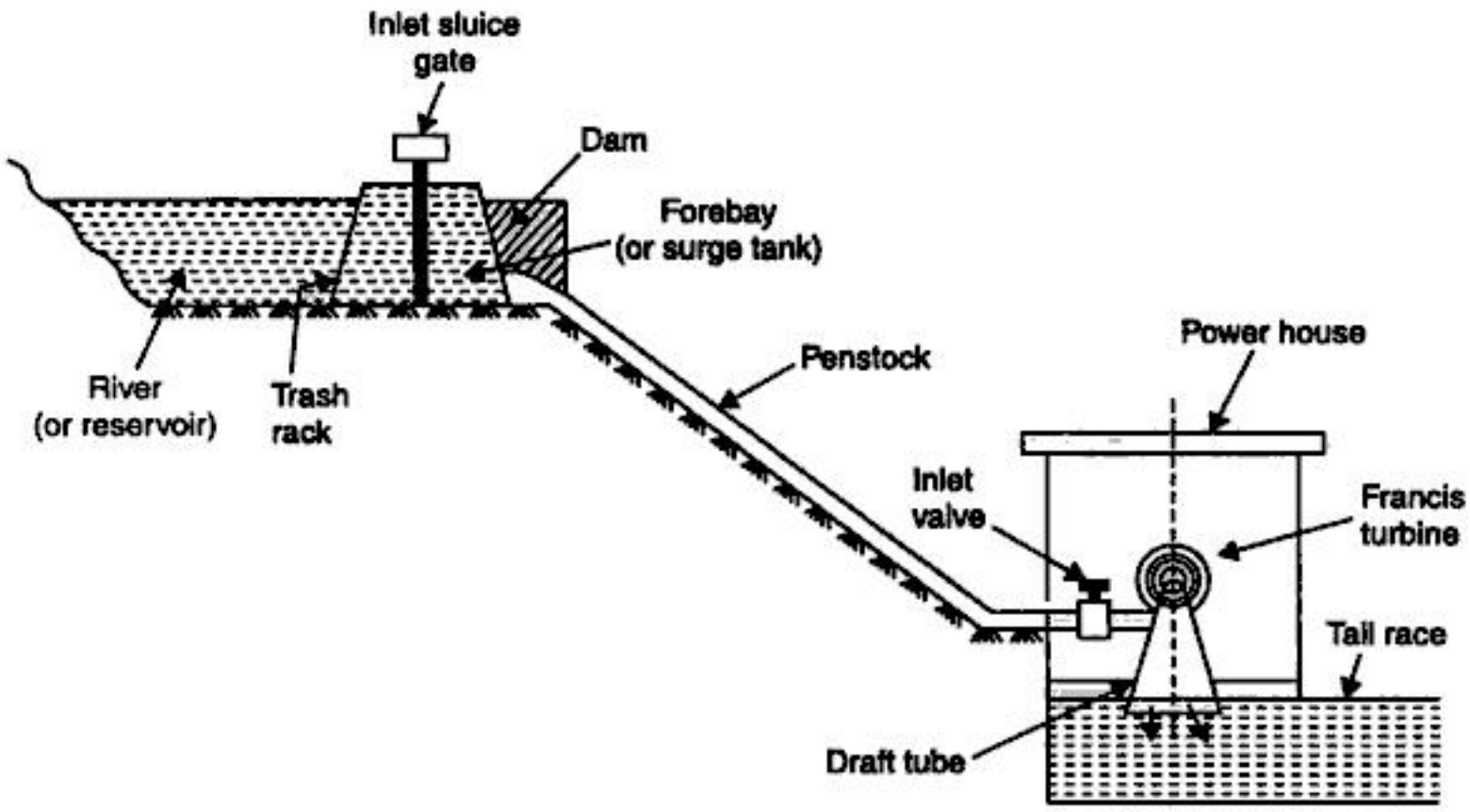

Fig. 5.3. Medium head power plant layout.

5.6.3. Low Head Power Plants

Refer Fig. 5.4. These plants usually consist of a dam across a river. A sideway stream diverges from the river at the dam. Over this stream the power house is constructed. Later this channel joins the river further downstream. This type of plant uses vertical shaft Francis turbine or Kaplan turbine.

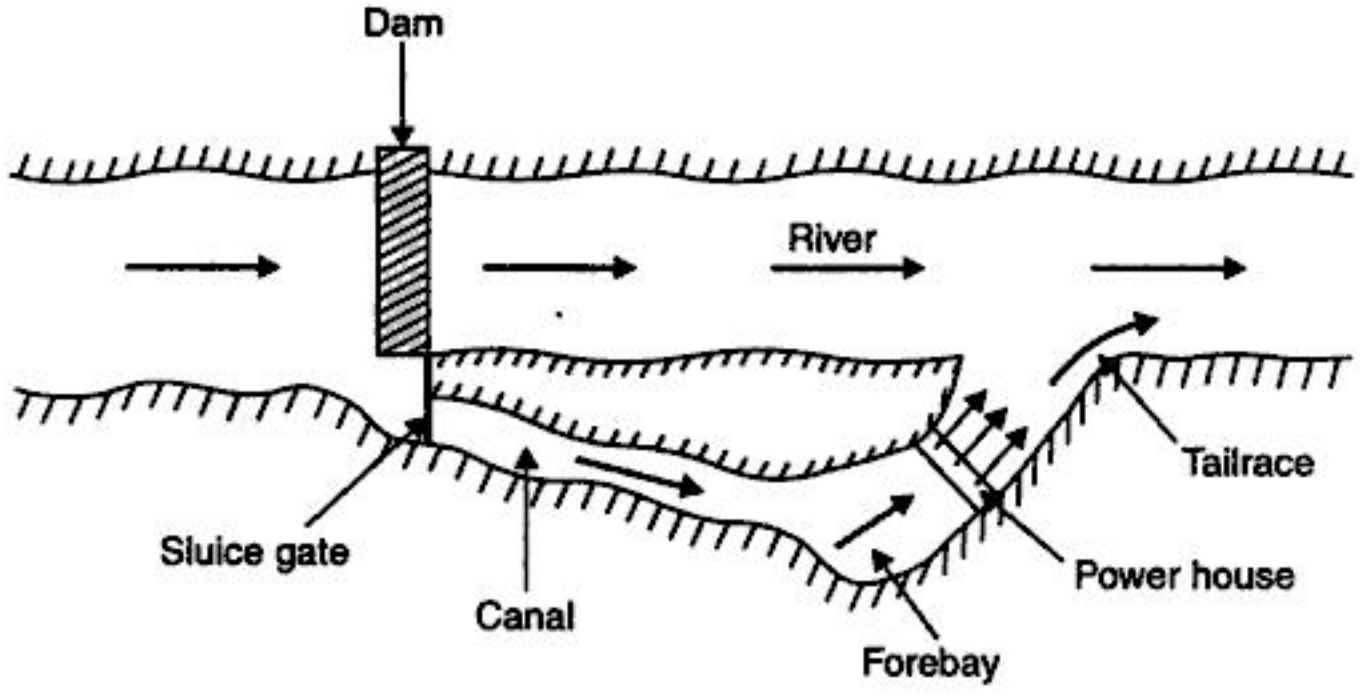

Fig. 5.4. Low head power plant layout.

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B. *According to the nature of load :*

5.6.4. Base Load Plants

The plants which cater to the base load of the system are called **base load plants.** These plants are required to *supply a constant power when connected to the grid.* Thus they *run without stop* and are often remote-controlled with which *least staff* is *required for such plants.* Run-of-river plants without pondage may sometimes work as baseload plant, but the firm capacity in such cases, will be much less.

5.6.5. Peak Load Plants

The plants which can supply the power during peak loads are known as **peak load plants.** Some of such plants supply the power during average load but also supply peak load as and when it is there ; whereas other peak load plants are required to work during peak load hours only. The run-of-river plants may be made for the peak load by providing pondage.

C. *According to the quantity of water available :*

5.6.6. Run-of-river Plants without Pondage

A run-of-river plant without pondage, as the name indicates, does not store water and uses the water as it comes. There is *no control on flow of water* so that during high floods or low loads water is wasted while during low run-off the plant capacity is considerably reduced. *Due to non-uniformity of supply and lack of assistance from a firm capacity the utility of these plants is much less* than those of other types. The head on which these plants work *varies considerably*. Such a plant can be made a great deal more useful by providing sufficient storage at the plant to take care of the hourly fluctuations in load. This lends some *firm capacity* to the plant. During good flow conditions these plants may cater to base load of the system, when flow reduces they may supply the peak demands. *Head water elevation for plant fluctuates with the flow conditions*. These plants without storage may sometimes be made to supply the base load, but the firm capacity depends on the minimum flow of river. The run-of-river plant may be made for load service with pondage, though storage is usually seasonal.

5.6.7. Run-of-river Plants with Pondage

Pondage usually refers to the collection of water behind a dam at the plant and increases the stream capacity for a short period, say a week. *Storage* means collection of water in up stream reservoirs and this increases the capacity of the stream over an extended period of several months. Storage plants may work satisfactorily as base load and peak load plants.

This type of plant, as compared to that without pondage, is *more reliable* and its generating capacity *is less dependent on the flow rates of water available.*

5.6.8. Storage Type Plants

A storage type plant is one with a reservoir of sufficiently large size to permit carry-over storage from the wet reason to the dry reason, and thus to supply firm flow substantially more than the minimum natural flow. This plant can be used as base load plant as well as peak load plant as water is available with control as required. The majority of hydro-electric plants are of this type.

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5.6.9. Pumped Storage Plants

Refer to Fig. 5.5.

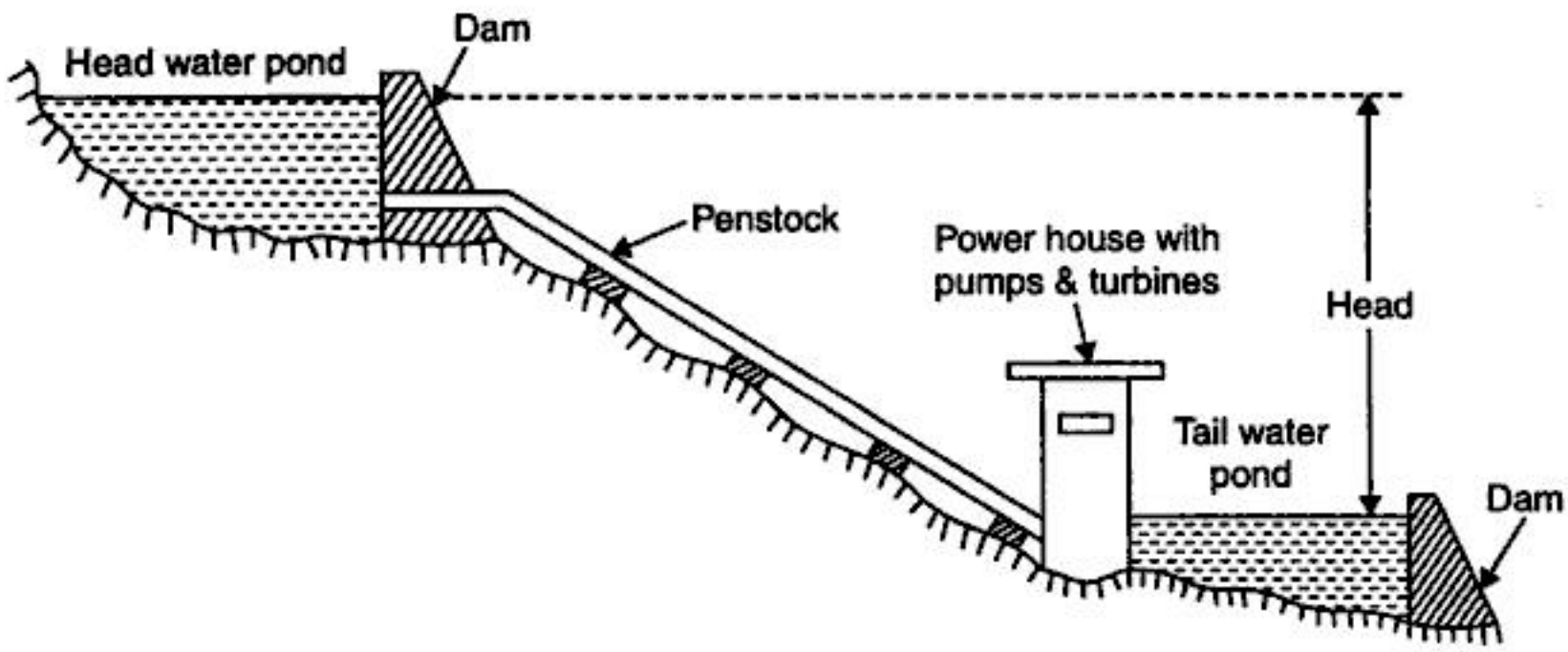

Fig. 5.5. Pumped storage plant.

Pumped storage plants are employed at the places where the quantity of water available for power generation is *inadequate*. Here the water passing through the turbines is stored in *'tail race pond'*. During low load periods this water is pumped back to the head reservoir using the extra energy available. This water can be again used for generating power during peak load periods. Pumping of water may be done seasonally or daily depending upon the conditions of the site and the nature of the load on the plant.

Such plants are *usually interconnected* with steam or diesel engine plants so that off peak capacity of interconnecting stations is used in pumping water and the same is used during peak load periods. Of course, the energy available from the quantity of water pumped by the plant is *less* than the energy input during pumped operation. Again while using pumped water the *power available is reduced* on account of losses occuring in primemovers.

Advantages. The pump storage plants entail the following *advantages* :

1. There is substantial increase in peak load capacity of the plant at comparatively low capital cost.
2. Due to load comparable to rated load on the plant, the operating efficiency of the plant is high.
3. There is an improvement in the load factor of the plant.
4. The energy available during peak load periods is higher than that of during off peak periods so that inspite of losses incurred in pumping there is *over-all gain*.
5. Load on the hydro-electric plant remains uniform.
6. The hydro-electric plant becomes partly independent of the stream flow conditions.

Under pump storage projects almost 70 percent power used in pumping the water can be recovered. In this field the use of *"Reversible Turbine Pump"* units is also worth noting. These units can be used as turbine while generating power and as pump while pumping water to storage. The generator in this case works as motor during reverse operation. The efficiency in such case is high and almost the same in both the operations. With the use of reversible turbine pump sets, additional capital investment on pump and its motor can be saved and the scheme can be worked more economically.

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5.6.10. Mini and Microhydel Plants

In order to meet with the present energy crisis partly, a solution is to develop *mini* (5 m to 20 m head) and *micro* (less than 5 m head) hydel potential in our country. The low head hydro-potential is scattered in this country and estimated potential from such sites could be as much as 20,000 MW.

By proper planning and implementation, it is possible to commission a small hydro-generating set up of 5 MW within a period of one and half year against the period of a decade or two for large capacity power plants. Several such sets upto 1000 kW each have been already installed in Himachal Pradesh, U.P., Arunachal Pradesh, West Bengal and Bhutan.

To reduce the cost of micro-hydel stations than that of the cost of conventional installation the following *considerations are kept in view* :

1. The civil engineering work needs to be kept to a *minimum* and designed to fit in with already existing structures *e.g.*, irrigation, channels, locks, small dams etc.
2. The machines need to be manufactured in a small range of sizes of simplified design, allowing the use of unified tools and aimed at reducing the cost of manufacture.
3. These installations must be automatically controlled to reduce attending personnel.
4. The equipment must be simple and robust, with easy accessibility to essential parts for maintenance.
5. The units must be light and adequately subassembled for ease of handling and transport and to keep down erection and dismantling costs.

Micro-hydel plants (micro-stations) *make use of standardised bulb sets with unit output ranging from 100 to 1000 kW working under heads between 1.5 to 10 metres.*

5.7. HYDRAULIC TURBINES

A hydraulic turbine converts the potential energy of water into mechanical energy which in turn is utilised to run an electric generator to get electric energy.

5.7.1. Classification of Hydraulic Turbines

The hydraulic turbines are *classified* as follows :

(*i*) According to the head and quantity of water available.

(*ii*) According to the name of the originator.

(*iii*) According to the action of water on the moving blades.

(*iv*) According to the direction of flow of water in the runner.

(*v*) According to the disposition of the turbine shaft.

(*vi*) According to the specific speed N_s.

1. According to the head and quantity of water available :

(*i*) *Impulse turbine*—requires *high head* and *small quantity of flow*.

(*ii*) *Reaction turbine*—requires *low head* and *high rate of flow*.

Actually there are two types of reaction turbines, one for medium head and medium flow and the other for low head and large flow.

2. According to the name of the originator :

(*i*) *Pelton turbine*—named after Lester Allen Pelton of California (USA). It is an impulse type of turbine and is used for *high head* and *low discharge*.

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B. Propeller and Kaplan turbines

- The need to utilize low heads where large volumes of water are available makes it essential to provide a large flow area and to run the machine at very low speeds. The propeller turbine is a reaction turbine used for heads between 4 m and 80 m, and has a specific speed ranging from 300 to 1000. It is purely *axial-flow* device providing the largest possible flow area that will utilize a large volume of water and still obtain flow velocities which are not too large.
- The propeller turbine (Fig. 5.9) consists of an axial-flow runner with four to six or at most ten blades of air-foil shape. The spiral casing and guide blades are similar to those in Francis turbines. In the **propeller turbine** as in Francis turbine the runner blades are *fixed* and *non-adjustable*. However in a *Kaplan turbine* (Fig. 5.10), which is modification of propeller turbine the runner blades are *adjustable and can be rotated about pivots fixed to the boss of the runner. The blades are adjusted automatically by servomechanism so that at all loads the flow enters them without shock.*
- Kaplan turbines have taken the place of Francis turbines for certain medium head installations. Kaplan turbines with sloping guide vanes to reduce the overall dimensions are being used.

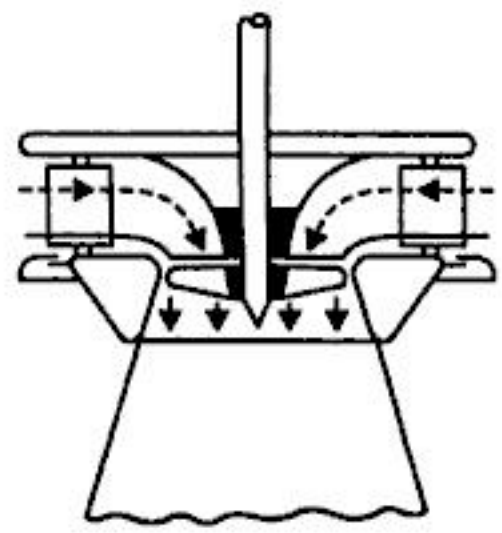
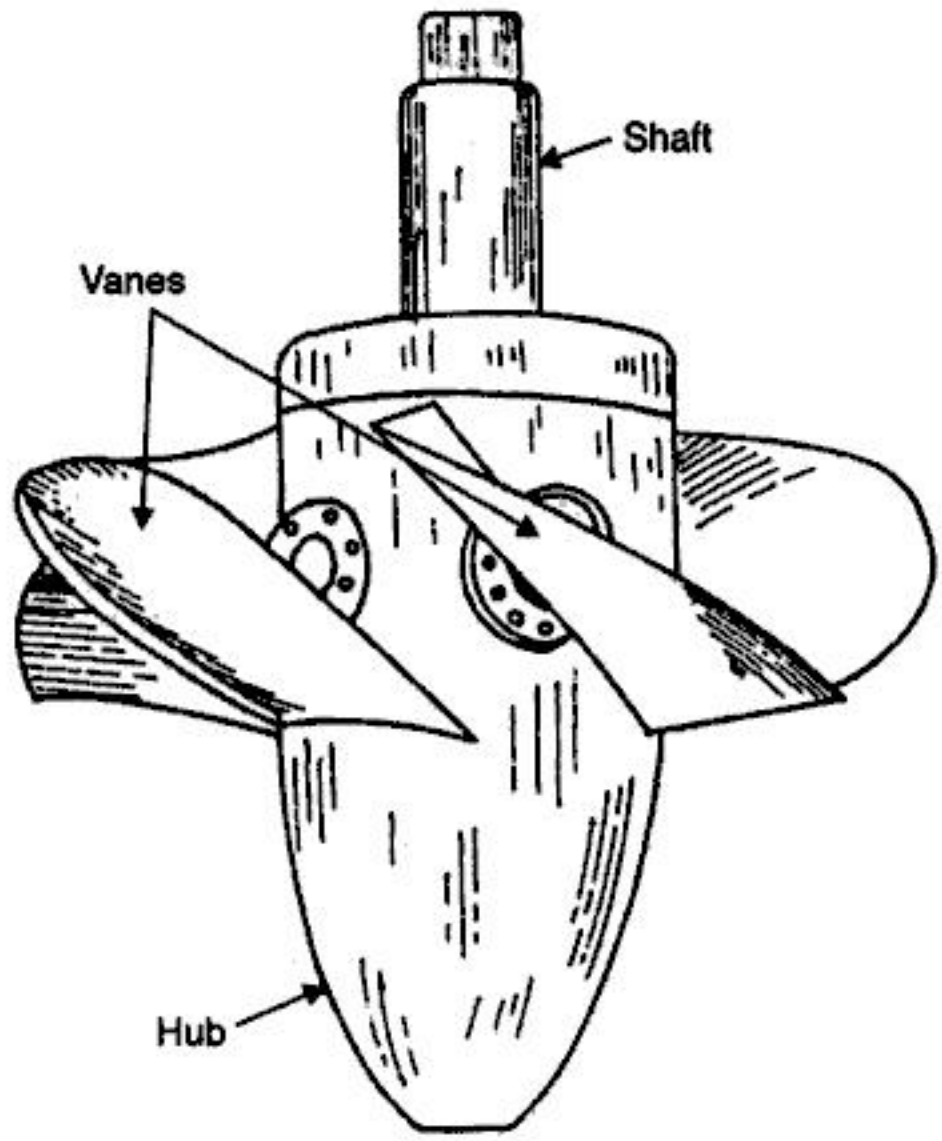


Fig. 5.9. Propeller turbine.



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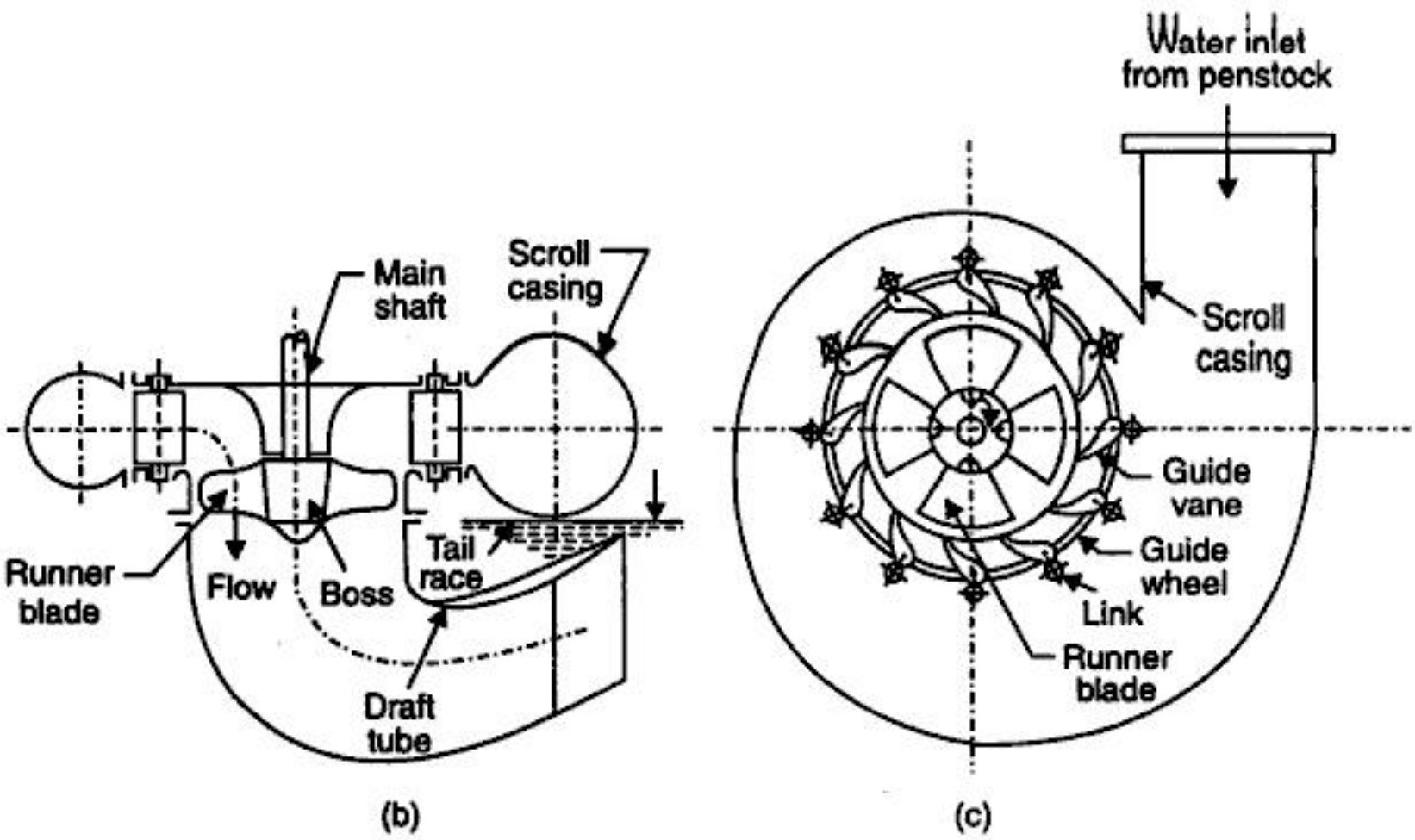

Fig. 5.10. Schematic diagram of a Kaplan turbine.

Fig. 5.11 shows the comparison of efficiencies of propeller (fixed blades) and Kaplan turbines.

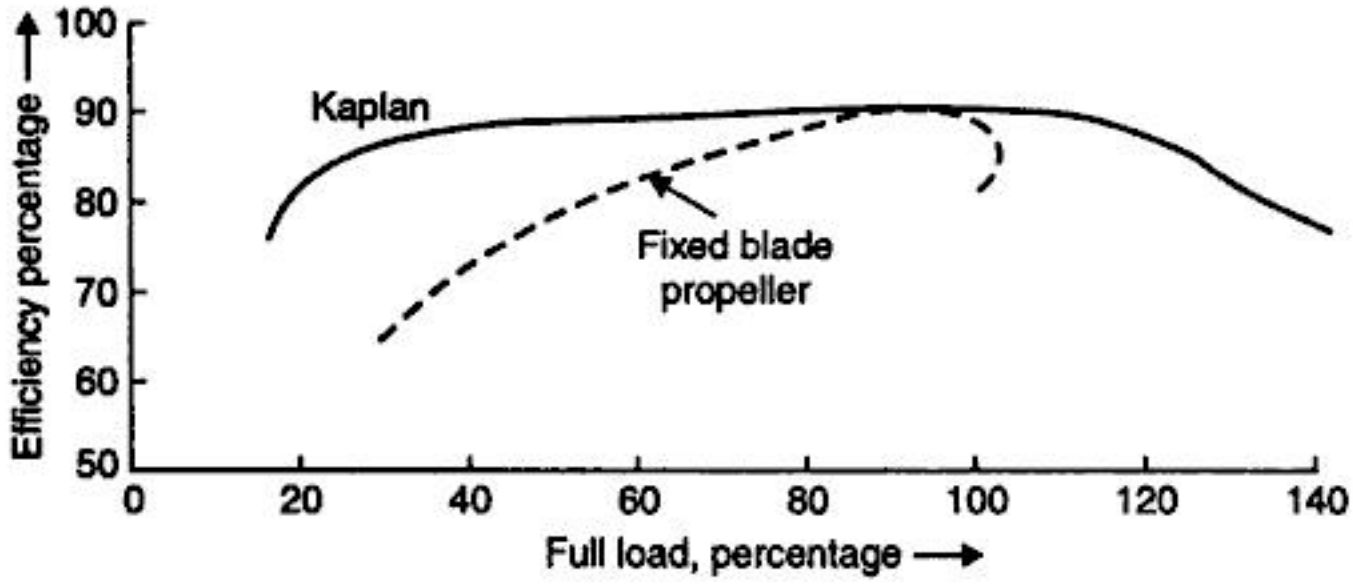

Fig. 5.11. Comparison of efficiencies of propeller (fixed blades) and Kaplan turbines.

C. Tubular (or Bulb) turbines

- Kaplan turbine when employed for very low head has to be installed below the tail race level, thus requiring a *deep excavation*. Further for Kaplan turbine installation there are a number of bends at inlet casing and the draft tube of elbow type through which the water flows describing 'Z' path giving rise to *continuous losses at the bends*. Whenever the turbine is repaired or dismantled, the generator has to be removed first. The cost of turbine and that of civil engineering works using conventional Kaplan turbine with deep excavation is very high. The efficiency of such plants working under low head is less due to excessive losses at the bends. Therefore, efforts have been made to *reduce the overall cost* and *improve the efficiency of the power plant* keeping these two things in view.
- In 1937 Arno Fischer developed in Germany a modified axial flow turbine which is known as *tubular turbine*. The turbo-generator set using tubular turbine has an outer casing having the shape of a bulb. Such a set is now termed as *bulb set* and the turbine used for

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the set is called a *bulb turbine.* The bulb unit is a water tight assembly of turbine and generator with horizontal axis, submerged in a stream of water. The economical harnessing of fairly low heads on major rivers is now possible with high-output bulb turbines.

Fig. 5.12 shows a power station (87300 kW) under a head of 10 m, provided with six 14550 kW bulb sets running at 125 r.p.m.

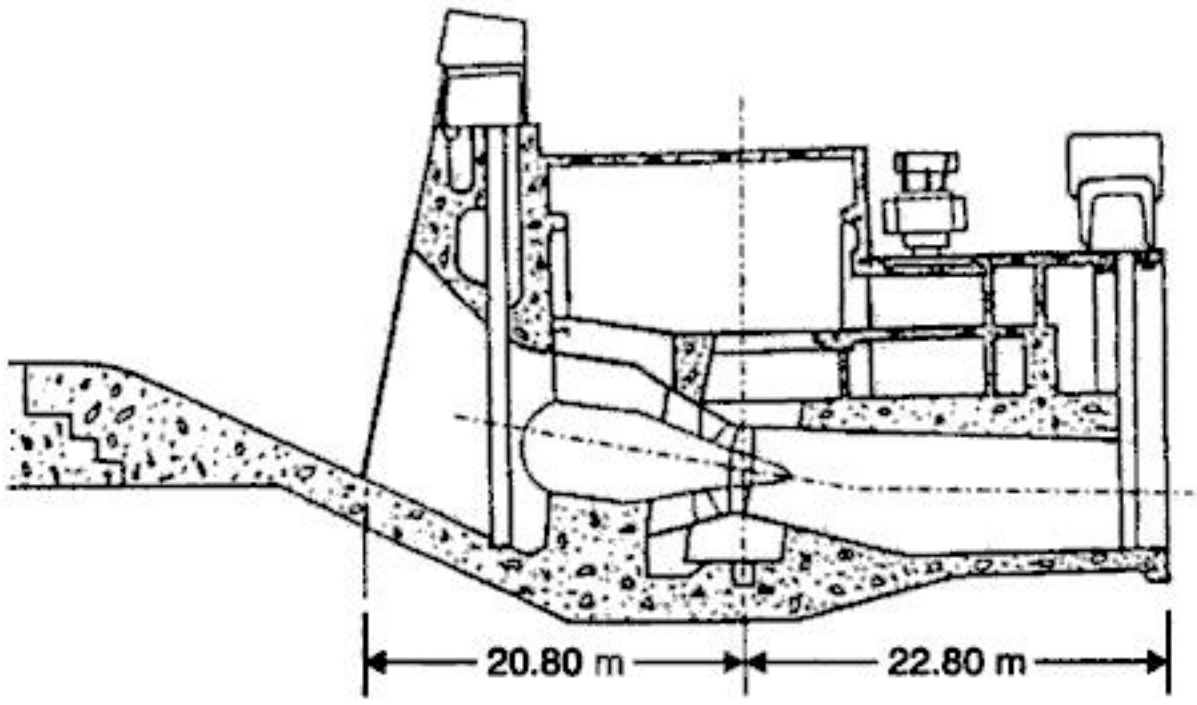

Fig. 5.12. Power station—using bulb turbines.

Comparison of hydraulic turbines :

I. *Francis turbine versus Pelton wheel :*

The Francis turbine claims the following *advantages* over Pelton wheel :

1. In Francis turbine the variation in the operating head can be more easily controlled.
2. In Francis turbine the ratio of maximum and minimum operating heads can be even two.
3. The operating head can be utilized even when the variation in the tail water level is relatively large when compared to the total head.
4. The mechanical efficiency of Pelton decreases faster with wear than Francis.
5. The size of the runner, generator and powerhouse required is small and economical if the Francis turbine is used instead of Pelton wheel for same power generation.

Drawbacks of Francis turbine :

As compared with Pelton wheel, the Francis turbine has the following *drawbacks* :

1. Water which is not clean can cause very rapid wear in high head Francis turbine.
2. The overhaul and inspection is much more difficult comparatively.
3. Cavitation is an ever-present danger.
4. The water hammer effect is more troublesome with Francis turbine.
5. If Francis turbine is run below 50% head for a long period it will not only lose its efficiency but also the cavitation danger will become more serious.

II. *Kaplan verses Francis turbine :*

Kaplan turbine claims the following *advantages* over Francis turbine :

1. For the same power developed Kaplan turbine is more compact in construction and smaller in size.
2. Part-load efficiency is considerably high.
3. Low frictional losses (because of small number of blades used).

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5.7.3. Specific Speed of a Turbine

The ***specific speed*** of a turbine is defined *as the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening etc., with the actual turbine but of such a size that it will develop unit horse power when working under unit head.*

$$\text{Specific speed } N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

(where P is in kW and H in metres)

[N_s (S.I. Units) = 0.86 N_s (metric)]

Specific speed plays an important role for *selecting the type of the turbine.* Also the *performance of a turbine can be predicted* by knowing the specific speed of the turbine.

To compare the characteristics of machines of different types, it is necessary to know a characteristic of an imaginary machine identical in shape. The imaginary turbine is called a *specific turbine.* The specific speed provides a means of comparing the speed of all types of hydraulic turbines on the basis of head and horse power capacity.

If a runner of *high specific speed* is used for a given head horse power output, the *overall cost* of installation is *lower*. The selection of *too* high specific speed reaction runner would reduce the size of the runner to such an extent that the discharge velocity of water into the throat of draft tube would be excessive. This is objectionable because a *vacuum* may be created in the extreme case.

The runner of *too high* specific speed with available head *increases the cost of turbine* on account of high mechanical strength required. The runner of *too low* specific speed with low available head *increases the cost of generator* due to the low turbine speed.

An increase in specific speed of turbine is accompanied by lower maximum efficiency and greater depth of excavation of the draft tube. In choosing a high specific speed turbine, an increase in cost of excavation of foundation and draft tube should be considered in addition to the efficiency. The weighted efficiency over the operating range of turbine is more important in the selection of a turbine instead of maximum efficiency.

Table 5.1 gives the specific speeds for various turbines.

Table 5.1. Specific speeds

Type of turbine		*Specific speed (N_s)*	
		M.K.S. Units	*S.I. Units*
Impulse (Pelton)	Slow	4—10	3.5—8.5
	Normal	10—25	8.5—21.5
	Fast	25—60	21.5—51.5
Radial and mixed flow (Francis and Deriaz)	Slow	60—150	51.5—130
	Normal	150—250	130—215
	Fast	250—400	215—345
Axial flow (Kaplan)	Slow	300—450	255—385
	Normal	450—700	385—600
	Fast	700—1000	600—860

5.7.4. Efficiencies of a Turbine

The important efficiencies of a turbine are as under :

1. Hydraulic efficiency, η_h

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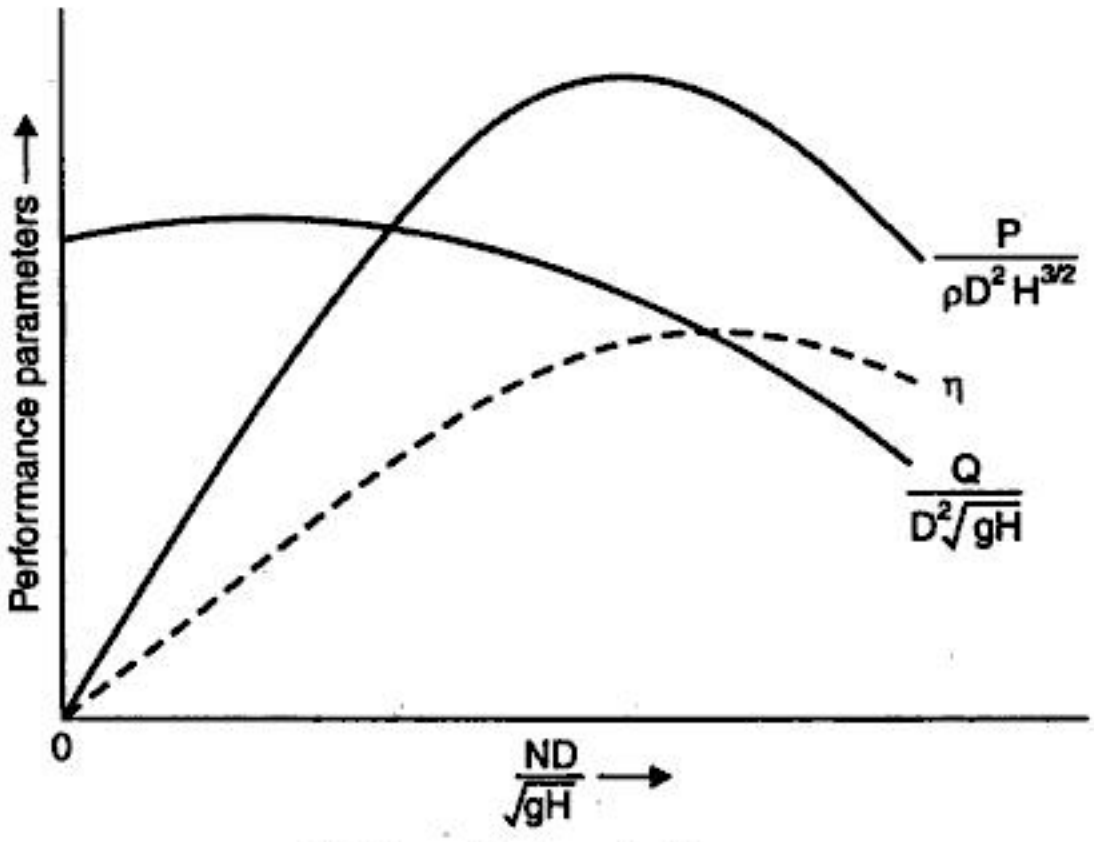
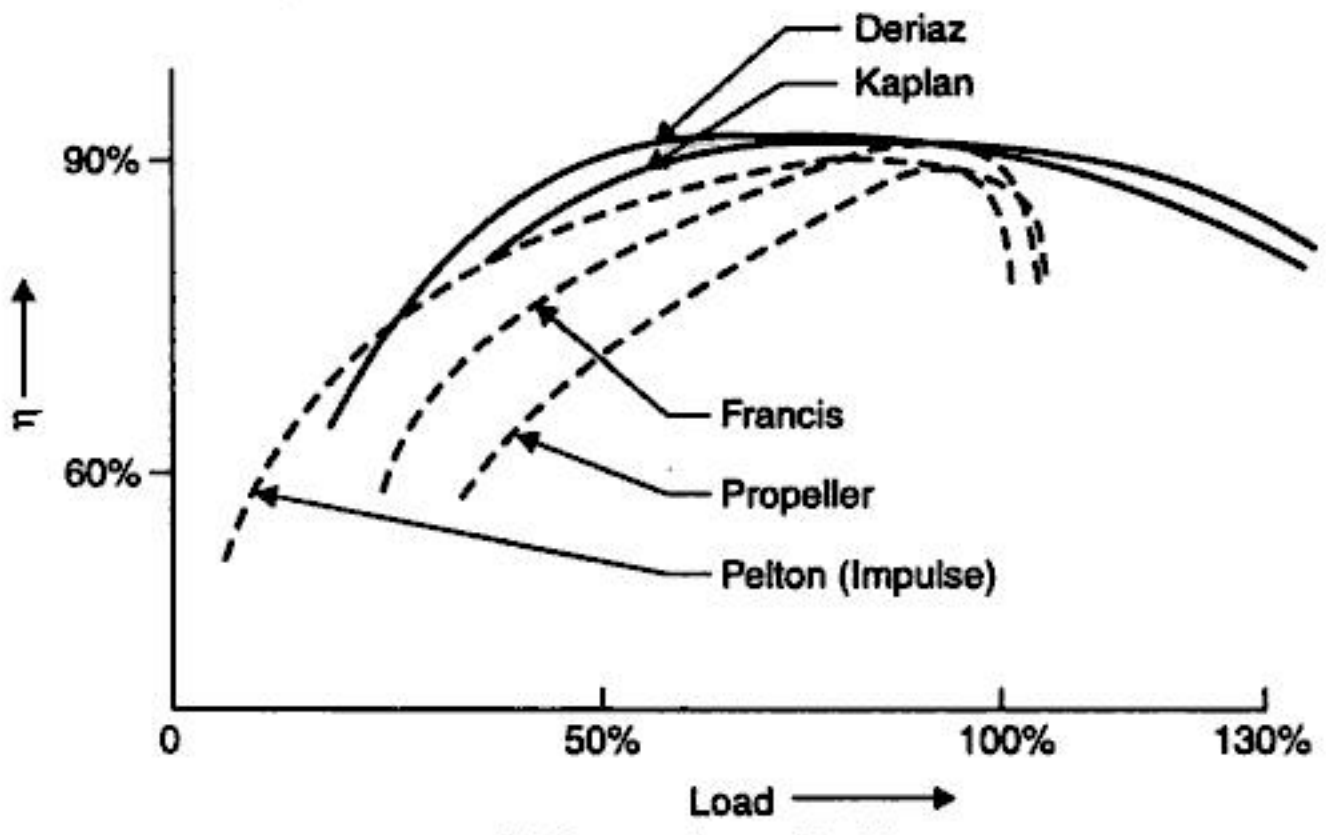
tive set of curves for different types of turbines is shown in Fig. 5.13 (*b*). It can be seen that the *Deriaz and Kaplan turbines have the highest efficiency in the entire load range*. This is due to the fact that the runner blades of these two types of turbines are *adjustable during operation*. Consequently the flow is efficient and well-guided by the runner blades at all flow conditions unlike the other turbines where the rotor-vane adjustability is not provided. The guide vanes of each of reaction turbines are adjusted for varying the discharge.



(a) Dimensionless turbine curves



(b) Comparison of turbines

Fig. 5.13. Performance of hydraulic turbines.

Fig. 5.14 and Fig. 5.15 shows the *main characteristic curves* for a Pelton wheel and reaction turbine respectively.

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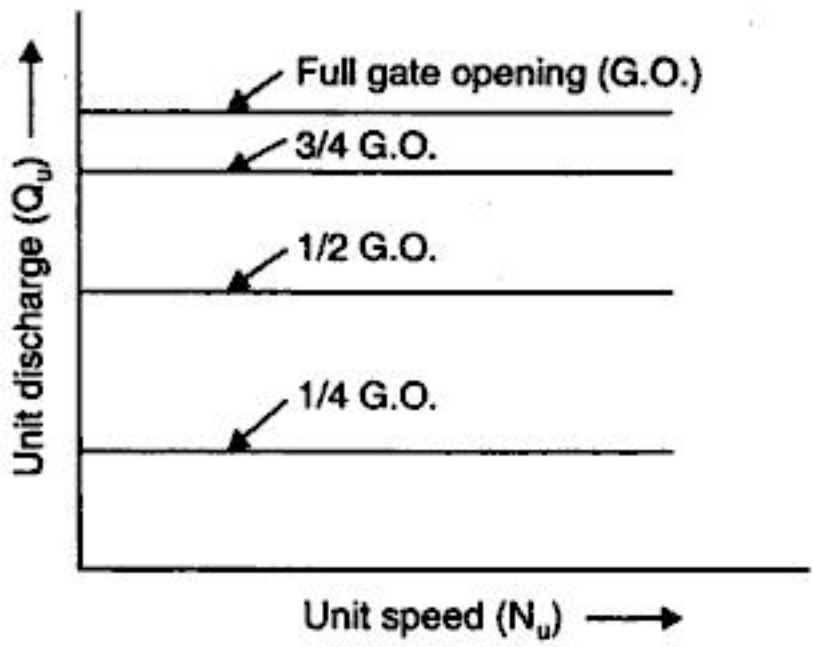


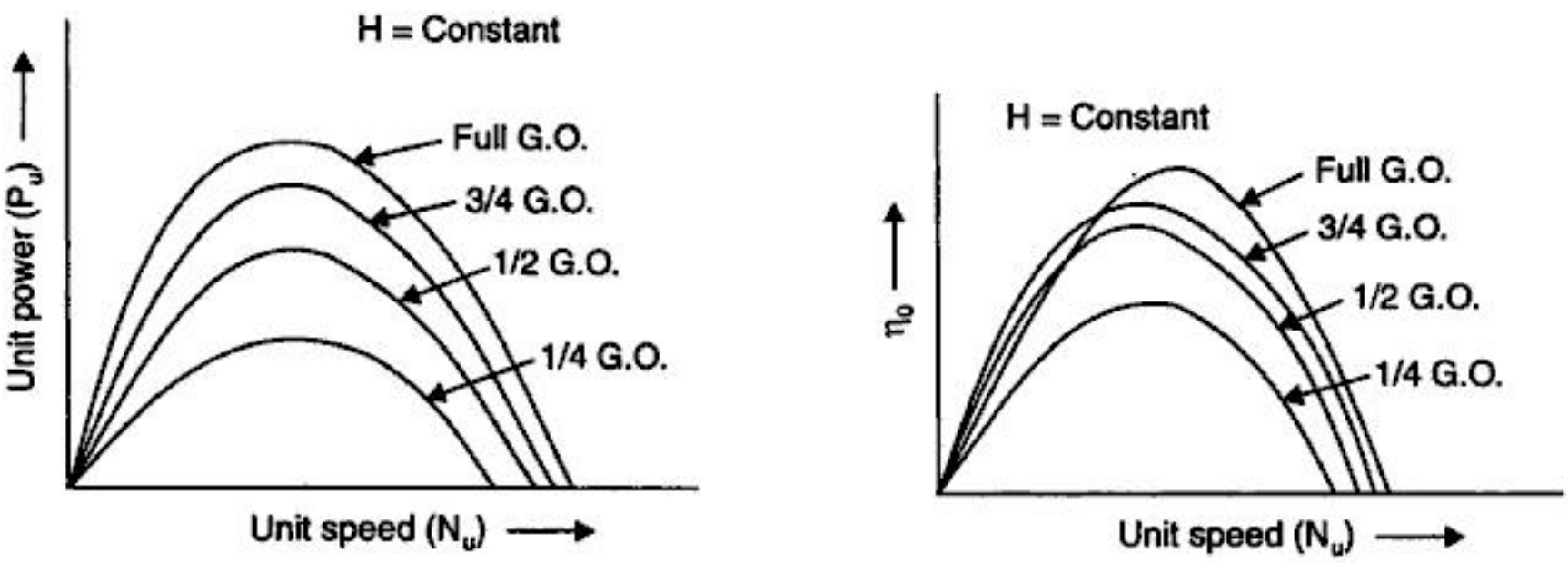
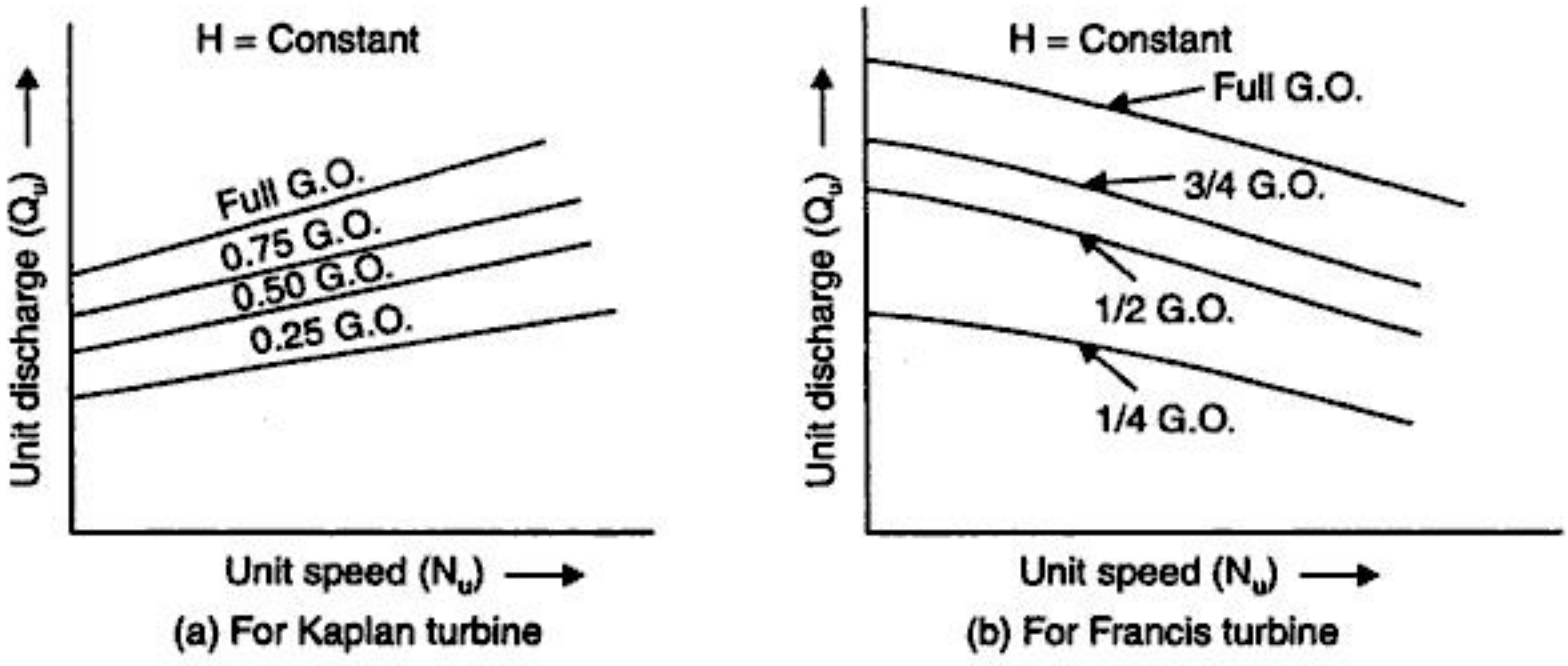


Fig. 5.14. Main characteristic curves for a Pelton wheel.



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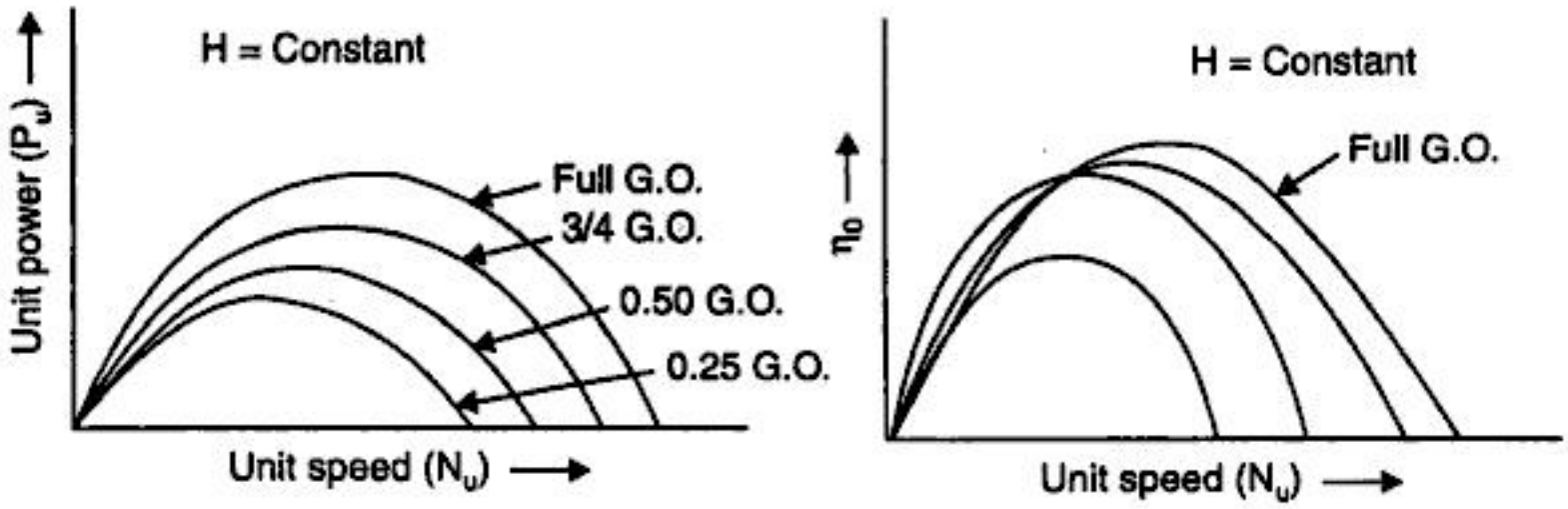

Fig. 5.15. Main characteristics of reaction turbines.

Efficiency load curves

The *efficiency load curves* of various types of *reaction turbines* are shown in Fig 5.16. The efficiency load curve of a Pelton turbine is shown in Fig. 5.17. The efficiency curve of a Pelton turbine remains slightly lower than that of a Francis turbine but is less affected by variation of load.

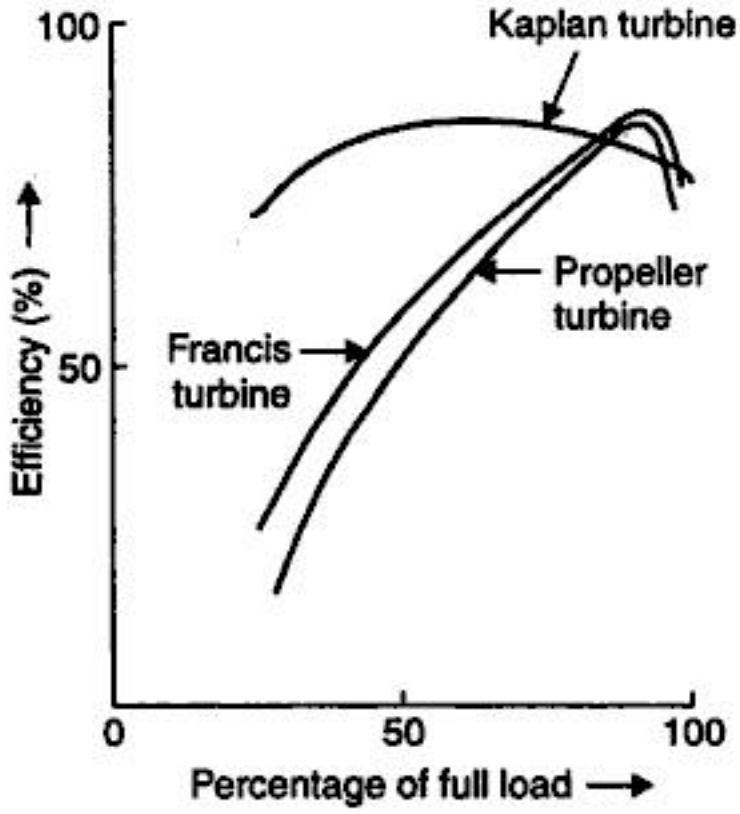

Fig. 5.16. Efficiency-load curves of reaction turbines.

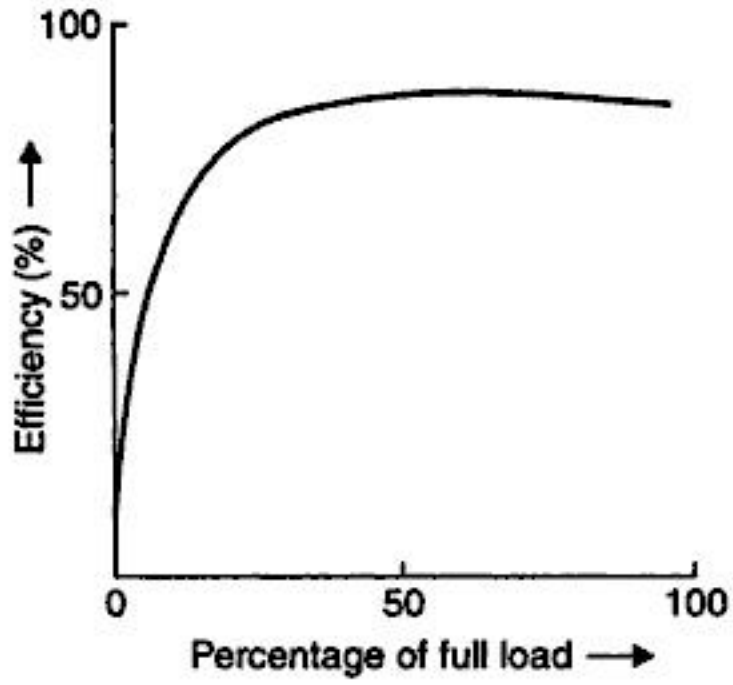

Fig. 5.17. Efficiency-load curve of a Pelton turbine.

5.7.7. Governing of Hydraulic Turbines

Governing of a hydraulic turbine means *speed regulation*. Under normal conditions the turbine should run at a constant speed irrespective of changes in load. This is achieved by means of a governor called oil pressure governor.

Governing of impulse turbine. The quantity of water rejected from the turbine nozzle and from striking the buckets may be regulated in one of the following ways :

1. Spear regulation.
2. Deflector regulation.
3. Combined spear and deflector regulation.

The spear and deflector in all cases are operated by the servomotor mechanism.

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Thus the *flow duration curve can be converted to a power duration with some other scale on the same graph.*

Flow duration curves are most useful in the following cases :

(*i*) *For preliminary studies* (*ii*) *For comparison between streams.*

Uses of flow duration curve :

1. A flow duration curve allows the evaluation of low level flows.

2. It is highly useful in the planning and design of water resources projects. In particular, for hydropower studies, the flow duration curve serves to determine the potential for *firm power* generation. In the case of a run-of-the-river plant, with no storage facilities, the firm power is usually computed on the basis of flow available 90 to 97 percent of the time. The *firm power* is also known as the *primary power*. *Secondary power* is the power generated at the plant utilising water other than that used for the generation of firm power.

3. If a sediment rating curve is available for the given stream, the flow duration curve can be converted into cumulative sediment transport curve by multiplying each flow rate by its rate of sediment transport. The area under this curve represents the total amount of sediment transported.

4. The flow duration curve also finds use in the design of drainage systems and in flood control studies.

5. A flow duration curve plotted on a log-log paper provides a qualitative description of the run-off variability in the stream. If the curve is having steep slope throughout, it indicates a stream with highly variable discharge. This is typical of the conditions where the flow is mainly from surface run-off. A flat slope indicates small variability which is a characteristic of the streams receiving both surface run-off and ground water run-off. A flat portion at the lower end of the curve indicates substantial contribution from ground water run-off, while the flat portion at the upper end of the curve is characteristic of streams with large flood plain storage, such as lakes and swaps, or where the high flows are mainly derived from snowmelt.

6. The shape of the flow duration curve may change with the length of record. This aspect of the flow duration curve can be utilised for extrapolation of short records.

Shortcomings/Defects of flow duration curve

1. It does not present the flows in natural source of occurrence.

2. It is also not possible to tell from flow duration curve whether the lowest flows occurred in consecutive periods or were scattered throughout the considered period.

5.22.6. Mass Curve

A **'mass curve'** *is the graph of the cumulative values of water quantity (run-off) against time.* A mass curve is an *integral curve of the hydrograph* which expresses the area under the hydrograph from one time to another.

It is a convenient device *to determine storage requirement* that is needed to produce a certain dependable flow from fluctuating discharge of a river by a reservoir.

Mass curve can also be used to solve the reserve problem of determining the maximum demand rate that can be maintained by a given storage volume. However, it is a trial and error procedure.

The mass curve *will always have a positive shape* but of a greater or less degree depending upon the variations in the quantity of inflow water available. The negative inclination of mass curve would show that the amount of water flowing in the reservoir was less than the loss due to evaporation and seepage.

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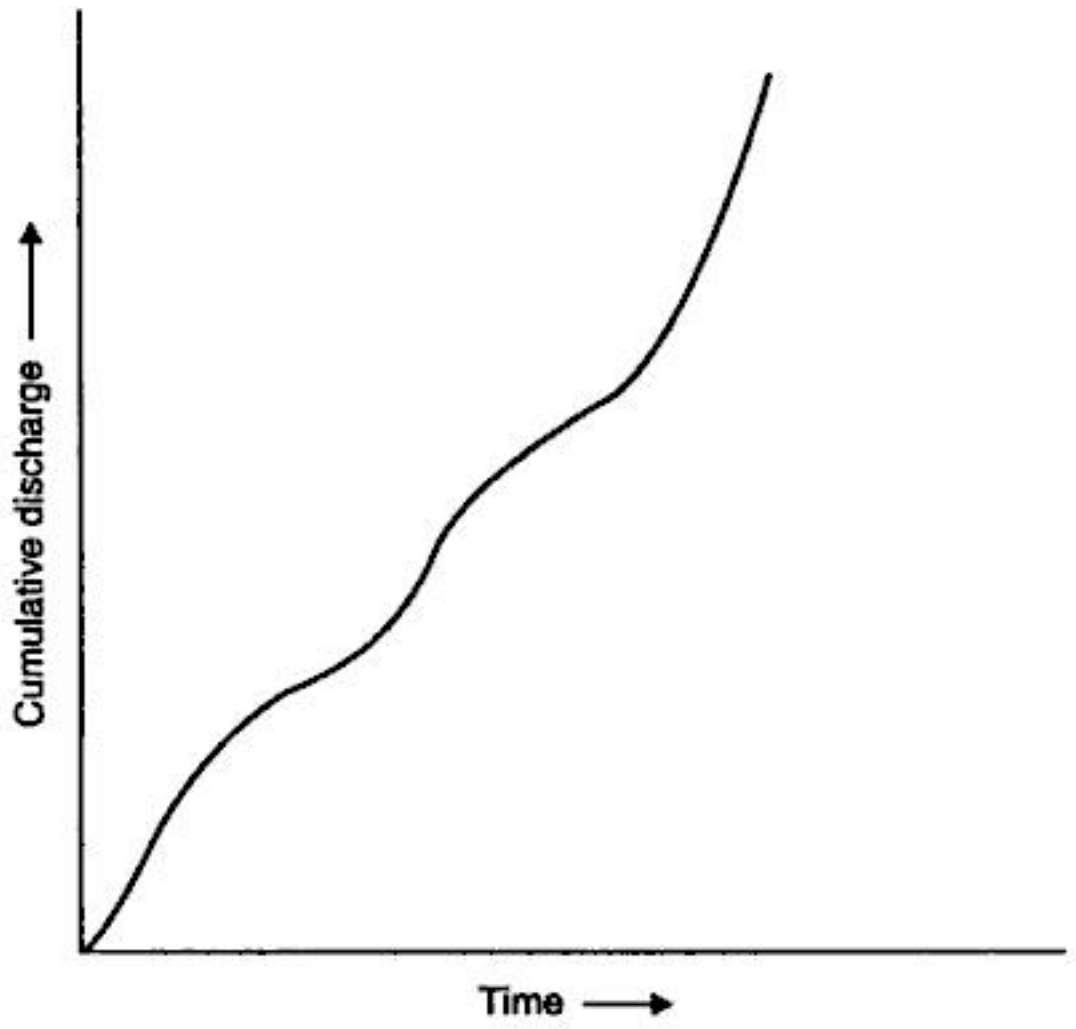

Fig. 5.26. Mass curve.

5.23. HYDRO-POWER DEVELOPMENT IN INDIA

Hydro-power is a renewable source of energy which entails many intrinsic advantages. In India the scope of water power development is tremendous. The first hydropower station in India dates back to year 1897 when a small power station of 200 kW capacity was constructed at Darjeeling. Since then many big and small hydropower stations have been installed in the country. Total hydro potential in our country is estimated to be equivalent to about 75000 MW at 60 percent load factor of which only about 20 percent has been exploited so far.

Important hydro plants in India

State/Name of power plant	*Installed capacity (MW)*
Andhra Pradesh	
Machkand (stage I and II)	114
Upper silern	120
Lower silern	600
Srisailam	770
Nagarjun sagar pumped storage	100
Assam	
Umiam	54
Gujarat	
Ukai	300
Himachal Pradesh	
Baira suil	200
Jammu and Kashmir	
Salal	270

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Karnataka	
Tungabhadra	72
Sharavati	890
Kailindi	396
Kerala	
Parambikulam-Aliyar	185
Sabarigiri	300
Idikki (Stage I)	390
Maharashtra	
Koyna (stages I, II and III)	860
Manipur	
Loktak	70
Orissa	
Hirakud (stages I and II)	270
Balimela	480
Punjab	
Bhakra Nangal	1084
Beas-Sutlej link	780
Rajasthan	
Chambal	287
Uttar Pradesh	
Rihand	300
Yamuna (stages I and II)	424
Tamil Nadu	
Kundah (stages I, II and III)	425
Kodiar	100

Although the present utilization of hydropower in over country is relatively small with the present tempo of development and need for power resources it would not be long before the available potential is fully harnessed. Hydro-field provides immense scope for sophisticated study requiring application of modern mathematical and operational research techniques with the help of computers.

Example 5.1. *The following data relate to a proposed hydro-electric station :*

Available head = 28 m ; Catchment area = 420 sq. km ; rainfall = 140 cm/year ; percentage of total rainfall utilized = 68% ; Penstock efficiency = 94% ; turbine efficiency = 80% ; generator efficiency = 84% and load factor = 44%.

(i) Calculate the power developed.

(ii) Suggest suitable machines and specify the same.

Solution. Head available, $H = 28$ m

Catchment area, $A = 420$ sq. km $(= 420 \times 10^6 \text{ m}^2)$

Rainfall $= 140$ cm/year $(= 1.4$ m$)$

Rainfall utilized, $h = 68\%$ of the total rainfall

$= (0.68 \times 1.4)$ m per year

Penstock efficiency, $\eta_p = 94\%$

Turbine efficiency, $\eta_t = 80\%$

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Generator efficiency, $\eta_g = 84\%$

Load factor $= 44\%$.

(*i*) Power developed, P :

Quantity of water available *per year*

$$= A \times h = (420 \times 10^6) \times (0.68 \times 1.4)$$

$$= 399.84 \times 10^6 \text{ m}^3$$

Hence the quantity of water available *per second,*

$$Q = \frac{399.84 \times 10^6}{(365 \times 24) \times 3600} = 12.6 \text{ m}^3$$

$\therefore$ $P = \eta_0 \times wQH$ (where, η_0 = Overall efficiency $= \eta_p \times \eta_t \times \eta_g$)

or $P = \eta_p \times \eta_t \times \eta_g \times wQH$

$$= 0.94 \times 0.8 \times 0.84 \times 9.81 \times 12.6 \times 28 = 2186 \text{ kW}$$

Hence *average output of generating units* = **2186 kW. (Ans.)**

(*ii*) Machines to be used :

Total ratings of generators $= \frac{2186}{0.44} = 4968$ kW

Providing *two machines* of equal rating,

Capacity of each unit $= \frac{4968}{2 \times 0.84} = 2957$ each.

As the available head is low, **Kaplan turbines** (propeller type) are suggested, each having a *generating capacity of* **2957 kW. (Ans.)**

Example 5.2. *The following data is available for a hydro-power plant :*

Available head = 140 m ; catchment area = 2000 sq. km ; annual average rainfall = 145 cm ; turbine efficiency = 85% ; generator efficiency = 90% ; percolation and evaporation losses = 16%.

Determine the following :

(i) Power developed.

(ii) Suggest type of turbine to be used if runner speed is to be kept below 240 r.p.m.

Solution. Head available, $H = 140$ m

Catchment area, $A = 200$ sq. km $(= 200 \times 10^6 \text{ m}^2)$

Annual average rainfall, $h = 145$ cm $(= 1.45$ m$)$

Turbine efficiency, $\eta_t = 85\%$

Generator efficiency, $\eta_g = 90\%$

Percolation and evaporation losses, $z = 16\% = 0.16$

(*i*) Power developed, P :

Quantity of water available for power generation *per year*

$$= A \times h \times (1 - z)$$

$$= 200 \times 10^6 \times 1.45 \times (1 - 0.16) = 2.436 \times 10^8 \text{ m}^3/\text{year}$$

Hence, quantity of water available per second,

$$Q = \frac{2.436 \times 10^8}{(365 \times 24) \times 3600} = 7.72 \text{ m}^3/\text{s}$$

$\therefore$ $P = \eta_0 \times wQH$

$= \eta_t \times \eta_g \times wQH$

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$$= 0.85 \times 0.9 \times 9.81 \times 7.72 \times 140$$

$$= \mathbf{8111\ kW\ or\ 8.111\ MW.}\quad \textbf{(Ans.)}$$

(*ii*) **Type of turbine to be used :**

Specific speed, $$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{240\sqrt{8111}}{(140)^{5/4}} = 44.28 \text{ r.p.m.}$$

Single Pelton turbine with 4 jets can be used. Further, since head available is large and discharge is low, Pelton turbine will work satisfactorily.

Example 5.3. *(a) Name the common types of prime movers that are employed in a hydroelectric power plant and discuss the factors that govern their choice.*

(b) A hydroelectric station is to be designed to operate at a mean head of 205 m and supplied from a reservoir lake having a catchment area of 1000 km² with average annual rain fall of 125 cm of which 80% is available for power generation. The expected load factor at the plant is 75%. Allowing a head loss of 5 m and assuming efficiency of the turbine and generator to be respectively 90% and 95%, calculate suitable MW rating of the station. Comment also on the type of turbine to be installed.

(AMII Summer 2001)

Solution. (*a*) The following three different types of hydraulic turbines are used as prime movers in hydroelectric power plants :

(*i*) **Kaplan.** For heads lower than 30 m and for variable load operation. Fixed vane propellers are used for heads less than 70 m and for fairly constant load operations.

(*ii*) **Francis turbine.** Used for heads from 70 m to 500 m. It is a reaction type of turbine and mostly used inward flow. The efficiency of Francis turbine at full load is high. It is designed for higher speed.

(*iii*) **Pelton wheel.** Used for heads more than 500 m. Pelton wheel is invariably mounted with a horizontal shaft and has low number of revolutions per minute. The limiting power output for a pelton wheel is of the order of 65,000 H.P.

(*b*) *Given :* Gross head = 205 m ; Catchment area = 1000 km² ; Average annual rainfall = 125 cm = 0.125 m ; Load factor = 75% or 0.75 ; Loss of head = 5 m ; $\eta_T = 90\%$; $\eta_G = 95\%$.

Water available during the year = $(1000 \times 10^6) \times 1.25 \times 0.8 = 10^9$ m³.

∴ Quantity of water available per sec.

$$= \frac{10^9}{8760 \times 3600} = 31.7 \text{ m}^3/\text{s}$$

Available head, $H = 205 - 5 = 200$ m

Now, *Average power produced,* $P = wQH \times \eta_T \times \eta_G$ kW

$$= 9.81 \times 31.7 \times 200 \times 0.9 \times 0.95 = 53177 \text{ kN}$$

$$\simeq 53.2 \text{ MW} \qquad \text{(where, } w = 9.81 \text{ kN/m}^3\text{)}$$

With a load factor of 75%, *overall capacity of the station for which it should be designed*

$$= \frac{53.2}{0.75} = \mathbf{70.9\ MW.}\quad \textbf{(Ans.)}$$

The type of turbine for a head of 200 m recommended is **Francis turbine.** **(Ans.)**

Example 5.4. *(a) Discuss the function of 'surge tank' in a hydroelectric power plant.*

(b) What are pumped storage plants and where are they used ?

(c) What are the differences between a 'run-off-river plant' and a 'run-off-river plant with pondage' ?

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(d) The daily load curve data for a certain area is as follows :

12 MN–5 AM	:	*100 MW*
5 AM–8 AM	:	*120 MW*
8 AM–12 Noon	:	*250 MW*
12 Noon–1 PM	:	*100 MW*
1 PM–5 PM	:	*250 MW*
5 PM–9 PM	:	*350 MW*
9 PM–12 MN	:	*150 MW*

It is proposed to install a run-off-river plant with pondage and a steam plant for supplying the above load. The run-off data indicates that a flow of 50 m^3/sec is available. The head is 90 m. Hydro-plant efficiency is 90% and transmission losses 5%. Determine the capacity of the hydro-plant and the steam plant. The steam plant is located near the load centre. **(Banglore University)**

Solution. (*a*) **Surge tank** in *a hydroelectric power plant is an open tank which is often used with the pressure conduit of considerable length.* The main purpose of providing surge tank is to *reduce the distance between the free water surface and turbine, thereby reducing the water hammer effect on penstock and also protect upstream tunnel from high pressure rises.* It also *serves as a supply tank to the turbine when the water to the pipe is accelerating during increased load conditions and as a storage tank when the water is decelerating during reduced load conditions.*

(*b*) The **pump storage power plant** essentially consists of a head water pond and a tail water pond. During the off-peak periods of an interconnected power plant system consisting of steam and pump storage, the water from the tail water pond is pumped with the help of a pump using extra energy available from thermal power plant during off-peak hours. With surplus available energy during off-peak period, energy is stored in the form of hydraulic potential energy by lifting the water from lower level to upper level. The same stored hydraulic energy is used during peak load period by supplying the water from the upper basin to the water turbine through the penstocks.

These plants are used wherever *base load stations are thermal stations and water is also available for hydro-generation.*

(*c*) **Run of river plant without pondage** *does not store the water and uses the water as it comes.* This plant has no control over the river flow. Therefore water is wasted during low load and high flood conditions. During dry seasons, the capacity of the plant goes down due to the low flow rates of the water. The utility of these plants is very less compared with other plants due to non-uniformity of supply and lack of assurance for continuous constant supply.

Run of river plant with pondage is *provided with a pond* in which water is stored during off-peak periods and the stored water is utilized during peak hours of the same day. *Pondage increases the stream capacity for a short period.* This type of plant *can be used as base load or peak load plant.*

(*d*) *Given :* $Q = 50$ m^3/s ; $H = 90$ m ; Hydro-plant efficiency = 91% ; Transmission losses = 5%.

Capacity of the hydro-plant and steam plant :

Total electrical energy required in 24 hours

$$= 5 \times 100 + 3 \times 120 + 4 \times 250 + 1 \times 100 + 4 \times 250 + 4 \times 350 + 3 \times 150$$

$$= 500 + 360 + 1000 + 100 + 1000 + 1400 + 450 = 4810 \text{ MWh.}$$

The average output of hydro-plant,

$$P = wQH \times \eta \times 10^{-3} \text{ MW} = 9.81 \times 50 \times 90 \times 0.91 \times 10^{-3} = \mathbf{40 \text{ MW.}} \quad \textbf{(Ans.)}$$

Since the transmission losses are given as 5%, therefore, total generation required

$$= 4810 \times 1.05 = 5050 \text{ MWh.}$$

Hydro-plant generation capacity = $40 \times 24 = 960$ MWh.

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∴ The steam plant generating capacity required

$$= 5050 - 960 = 4090 \text{ MWh}$$

Assuming power required is for 24 hours,

$$\text{Steam plant-rating} = \frac{4090}{24} = \mathbf{170\ MW.}\quad \textbf{(Ans.)}$$

Example 5.5. *What is a pumped storage plant ? Explain the advantage of a pumped storage plant for short peak load operation. Compare its economics with an old steam plant.*

Solution. Pump storage plant *works as a peak load station.* In this station water is pumped into a high level reservoir at off-peak periods and is utilized to drive turbines and generate power when the peak of the system occurs.

The plant consists of a synchronous motor or an induction motor coupled on one side to a multistage centrifugal pump and on the other side to a turbine. During off-peak periods the water drives the pump and replenishes the reservoir. When the system peak occurs the motor runs as an alternator or an induction generator driven by turbine. The plant can change over from one function to another *i.e.* pumping to generating and vice versa very rapidly and the whole sequence of operation is automatically controlled. An induction generator always supplies the load at leading p.f. hence compensating the system p.f. The basic advantage of pumped storage may be justified because it permits available energy to be stored for later use when it is more valuable.

When an old steam plant is used for peak load operations as an alternative to a pumped storage plant, it is a costly proposition and more over it requires large starting time and shut down time. Hence old steam plants are not at all convenient for peak load demand. Further these systems can not be used in reversible mode as is possible with pumped storage plants.

HYDROLOGY

Example 5.6. *At a particular site the mean monthly discharge is as follows :*

Month	*Discharge, m^3/s*	*Month*	*Discharge, m^3/s*
January	*100*	*July*	*1000*
February	*225*	*August*	*1200*
March	*300*	*September*	*900*
April	*600*	*October*	*600*
May	*750*	*November*	*400*
June	*800*	*December*	*200*

Draw the following :

(i) Hydrograph

(ii) Flow duration curve.

Solution. (*i*) The **hydrograph** is plotted between discharge (m^3/sec) and time (months) as shown in Fig. 5.27.

(*ii*) **Flow duration curve :**

In order to draw *flow duration curve* it is essential to find the *length* of *time* during which certain flows are available, *e.g.*, 100 m^3/s is available for all 12 months, flow of 200 m^3/s for 11 months, 225 m^3/s for 10 months and so on. This information is indicated in the table below :

Discharge, m^3/s	*Length of time, months*	*%âge time*
100 (and more)	12	100
200 (and more)	11	91.7
225 (and more)	10	83.3

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300 (and more)	9	75.0
400 (and more)	8	66.7
600 (and more)	7	58.3
750 (and more)	5	41.7
800 (and more)	4	33.3
900 (and more)	3	25.0
1000 (and more)	2	16.7
1200 (and more)	1	8.3

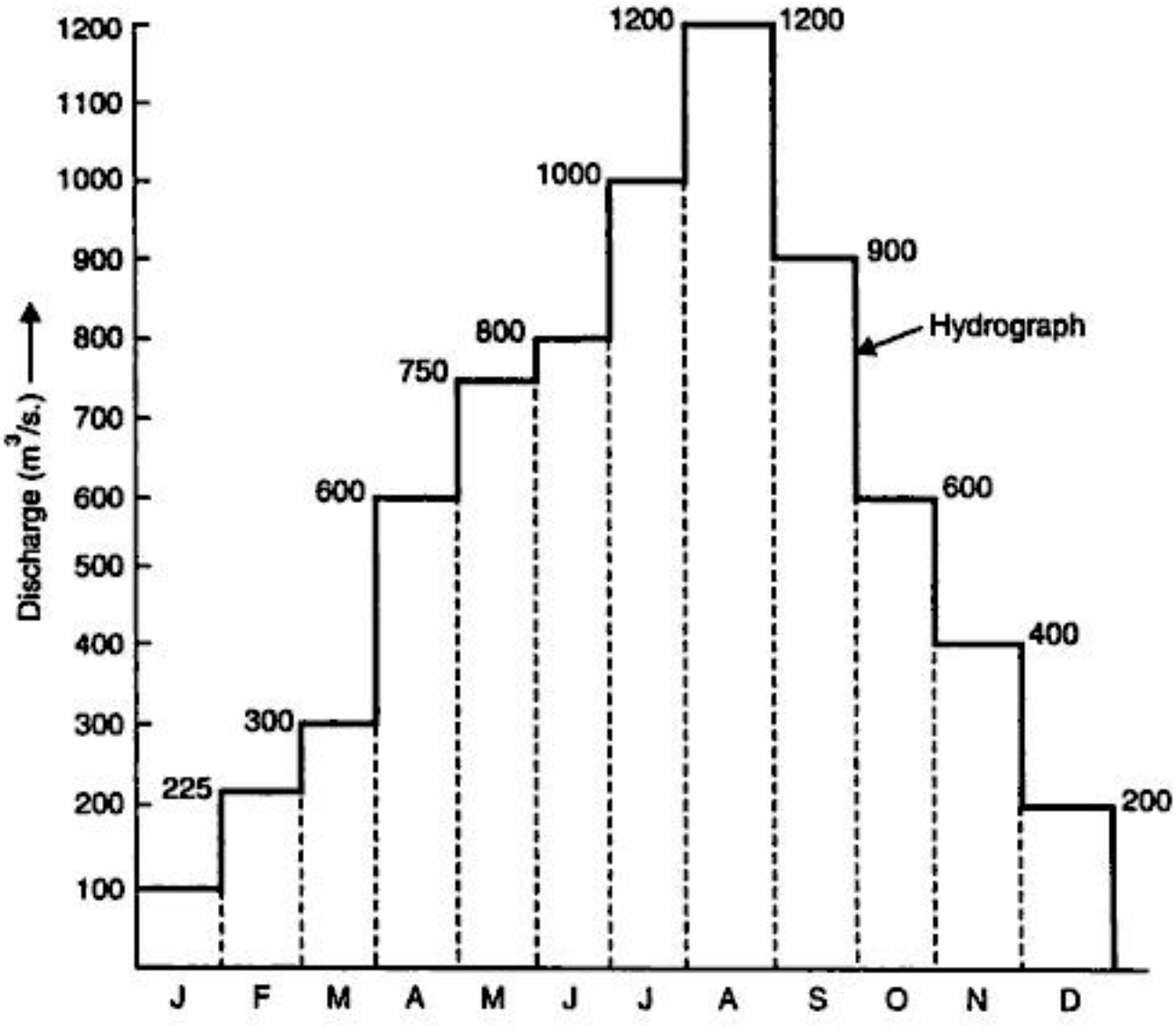

Fig. 5.27. Hydrograph.

The flow duration curve is then plotted as shown in Fig. 5.28.

Note. When selecting a suitable site for a hydropower plant the flow data for a number of years is collected and hydrographs and flow duration curves and the various periods are determined.

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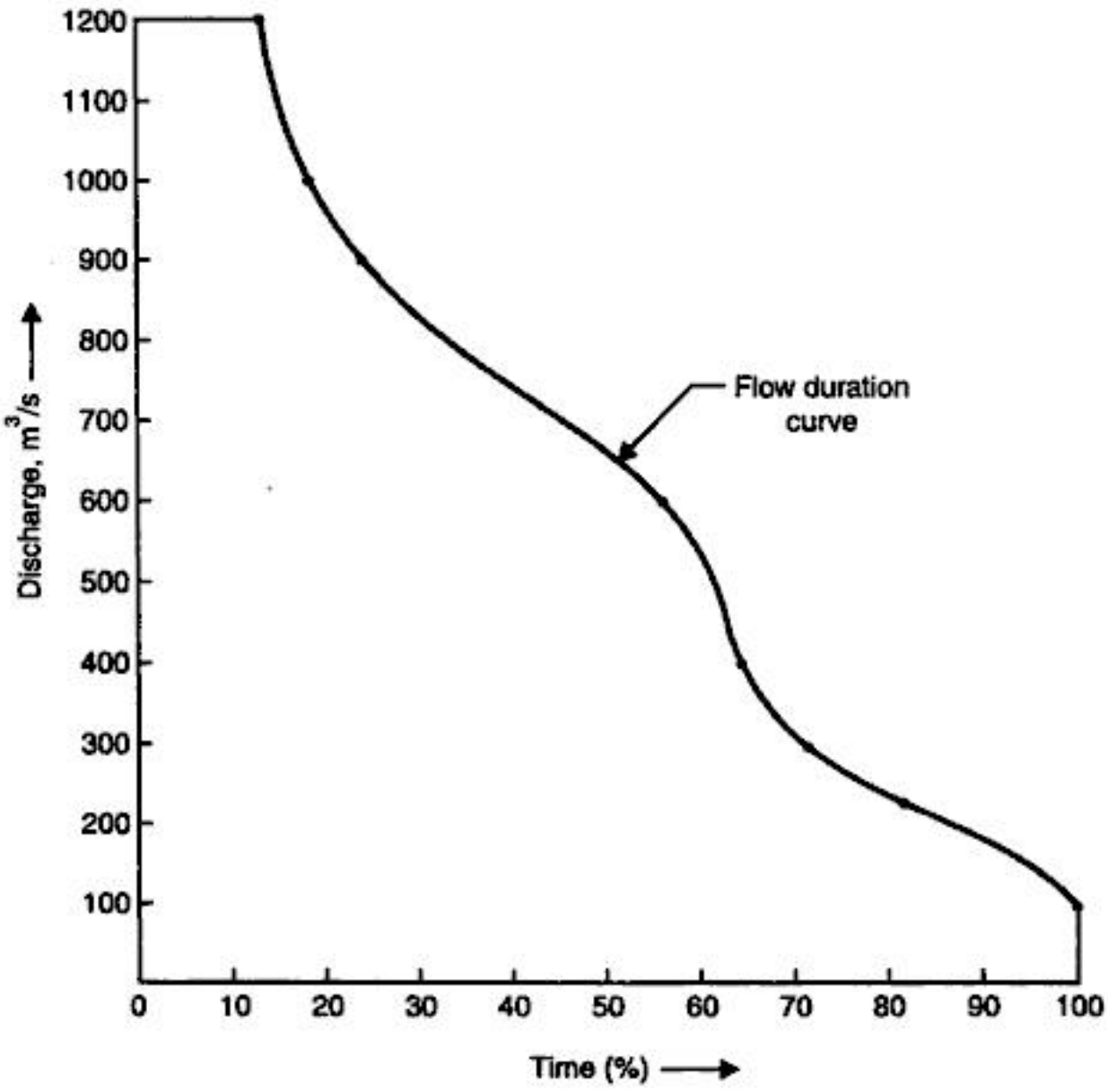

Fig. 5.28. Flow duration curve.

Example 5.7. *The runoff data of a river at a particular site is tabulated below :*

Month	*Mean discharge per month (millions of cum)*	*Month*	*Mean discharge per month (millions of cum)*
January	*40*	*July*	*75*
February	*25*	*August*	*100*
March	*20*	*September*	*110*
April	*10*	*October*	*60*
May	*0*	*November*	*50*
June	*50*	*December*	*40*

(i) Draw a hydrograph and find the mean flow,

(ii) Also draw the flow duration curve,

(iii) Find the power in MW available at mean flow if the head available is 80 m and overall efficiency of generation is 85%.

Take each month of 30 days.

Solution. *(i)* **Hydrograph :**

The *hydrograph* for the given data is drawn as shown in Fig. 5.29.

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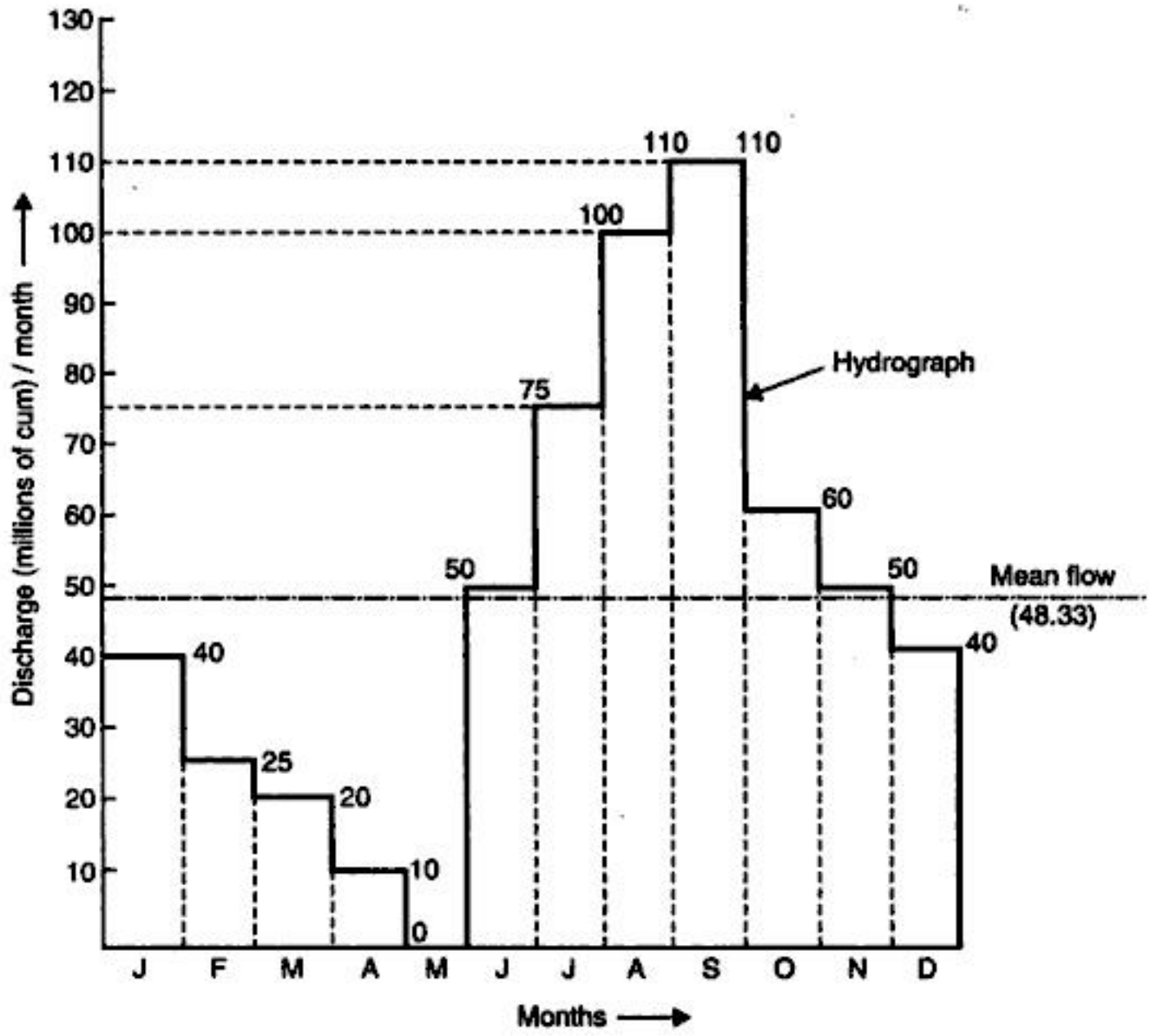

Fig. 5.29. Hydrograph.

The mean discharge for the given data

$$= \frac{40 + 25 + 20 + 10 + 0 + 50 + 75 + 100 + 110 + 60 + 50 + 40}{12}$$

$$= \frac{580}{12} = 48.33 \text{ millions of } m^3/\text{month}.$$

(*ii*) Flow duration curve :

To obtain the *flow duration curve* it is necessary to find the *lengths of time* during which certain flows are available. This information is tabulated, using the hydrograph, in the table below :

Discharge per month (millions of m^3)	*Total number of months during which flow is available*	*Percentage time*
0	12	100
10	11	91.7
20	10	83.3
25	9	75
40	8	66.7
50	6	50
60	4	33.3
75	3	25.0
100	2	16.7
110	1	8.3

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The flow duration curve can be drawn using the data tabulated, as shown in Fig. 5.30.

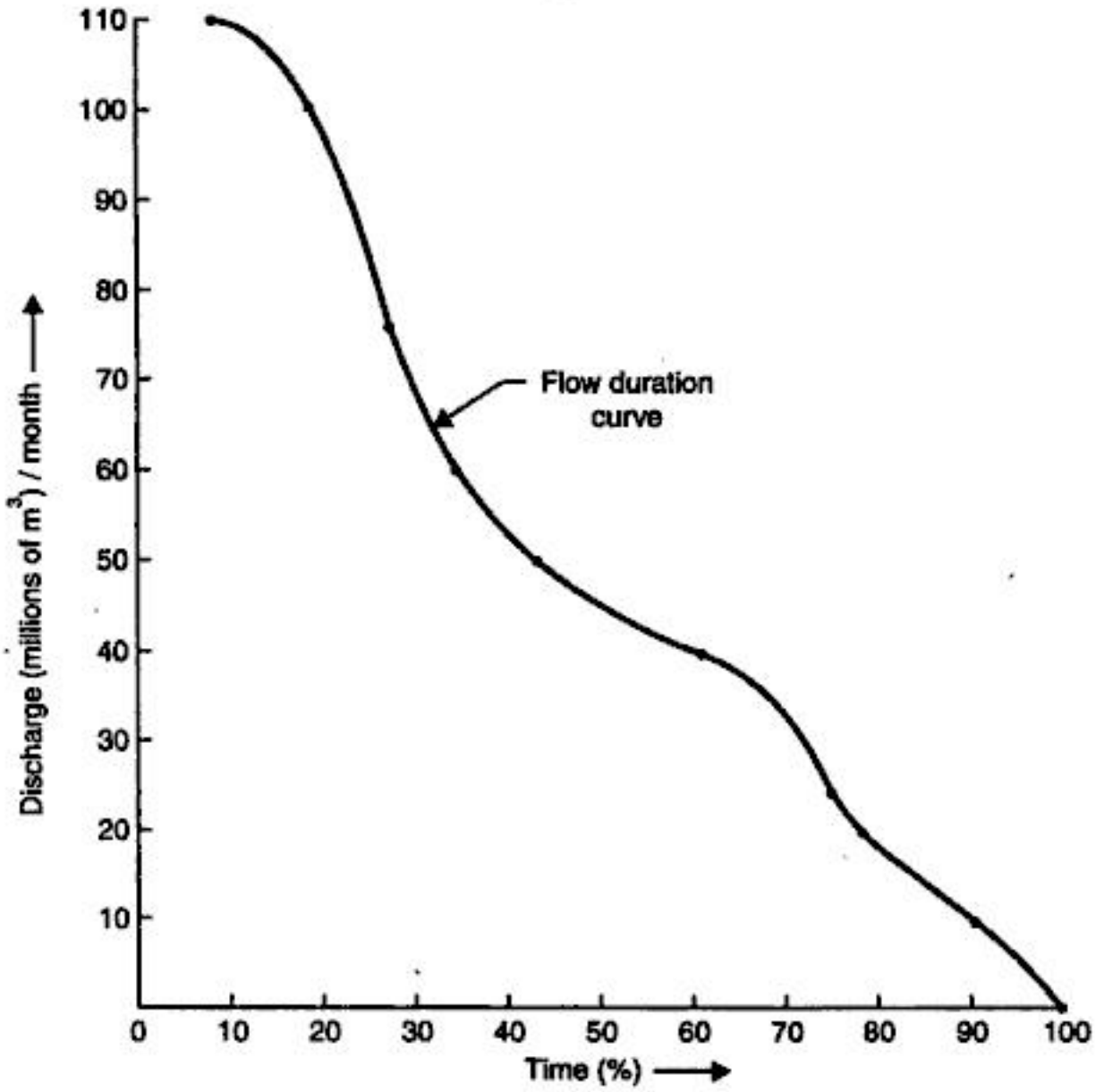

Fig. 5.30. Flow duration curve.

(*iii*) Average MW energy available :

$$= \eta_0 \, wQH \times \frac{1}{1000} \text{ MW} \qquad \text{(where } w = 9.81 \text{ kN/m}^3\text{)}$$

$$\left[\text{where } Q \text{ (discharge in m}^3/s) = \frac{48.33 \times 10^6}{30 \times 24 \times 3600}\right]$$

$$= 0.85 \times \frac{9.81 \times 48.33 \times 10^6 \times 80}{(30 \times 24 \times 3600)} \times \frac{1}{1000} \text{ MW}$$

$$= \mathbf{12.4 \text{ MW.}} \quad \textbf{(Ans.)}$$

HIGHLIGHTS

1. A *dam* is a barrier to confine or raise water for storage or diversion to create a hydraulic head.
2. A *canal* is an open waterway excavated in natural ground. A *flume* is an open channel excavated on the surface or supported above ground on a trestle. A *tunnel* is a closed channel excavated through a natural obstruction such as a ridge of higher land between the dam and the powerhouse.
3. A *surge tank* is a small reservoir or tank in which the water level rises or falls to reduce the pressure swings so that they are not transmitted in full to a closed circuit.
4. A *draft tube* serves the following two purposes :
   (*i*) It allows the turbine to be set above tail-water level, without loss of head, to facilitate inspection and maintenance.
   (*ii*) It regains, by diffuser action, the major portion of the kinetic energy delivered to it from the runner.

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5. The plants which cater to the base load of the system are called *'base load plants'* whereas the plants which can supply the power during peak loads are known as *peak load plants.*
6. Microhydel plants (microstations) make use of standardized *bulb sets* with unit output ranging from 100 to 1000 kW working under heads between 1.5 to 10 metres.
7. The *specific speed* of a turbine is defined as the speed of a geometrically similar turbine that would develop one brake horse power under a head of one metre,
8. The *Pelton* turbine is a tangential flow impulse turbine. The pressure over the Pelton wheel is constant and equal to atmosphere, so that energy transfer occurs due to purely impulse action.
9. The modern *Francis* water turbine is an inward mixed flow reaction turbine. It operates under medium heads and also requires medium quantity of water.
10. In the *propeller turbine* the runner blades are fixed and non-adjustable. In *Kaplan turbine*, which is a modification of propeller turbine the runner blades are adjustable and can be rotated about the pivots fixed to the boss of the runner.
11. *'Cavitation'* may be defined as the phenomenon which manifests itself in the pitting of the metallic surfaces of turbine parts because of formation of cavities.
12. *'Hydrology'* may be defined as the science which deals with the depletion and replenishment of water resources.
13. Run-off includes all the water flowing in the stream channel at any given section. It can be measured by the following methods :
    (*i*) From rainfall records (*ii*) Empirical formulae
    (*iii*) Run-off curves and tables (*iv*) Discharge observation method.
14. *Hydrograph* is defined as a graph showing discharge (run-off) of flowing water with respect to time for a specified time. It indicates the power available from the stream at different times of day, week or year.
15. *Flow duration curve* represents the run-off data for the given time. It is plotted between flow available during a period *versus* the fraction of time.
16. *Mass curve* is the graph of the cumulative values of water quantity (run-off) against time. It is an integral curve of the hydrograph which expresses the area under the hydrograph from one time to another.

THEORETICAL QUESTIONS

1. Give the application of hydro-electric plants.
2. Enumerate advantages and disadvantages of hydro-plants.
3. Enumerate and explain briefly the factors which should be considered while selecting the site for hydro-electric plant.
4. Enumerate essential elements of hydro-electric power plant.
5. What is a catchment area ?
6. What is a reservoir ?
7. What is a dam ? What are its various types ?
8. Explain briefly any two of the following dams :
   (*i*) Rockfill dams (*ii*) Buttress dams
   (*iii*) Timber dams.
9. What is a spillway ? Explain any two types of spillways.
10. What is the difference between canal, flume and tunnel ?
11. What is a surge tank ?
12. Explain with a neat diagram any one of the following surge tanks :
    (*i*) Inclined surge tank (*ii*) Restricted orifice surge tank
    (*iii*) Differential surge tank.
13. What are the functions of a draft tube ?
14. How are hydro-electric power plants classified ?
15. Explain an high head power plant giving its layout clearly.
16. Explain with a neat sketch a pumped storage plant.

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17. What is the function of a hydraulic turbine ? How are the turbines classified ?
18. Explain the working of a 'Pelton turbine' with the help of a neat diagram.
19. With the help of a schematic diagram explain the working of the modern Francis turbine.
20. What is a Kaplan turbine ? How does it differ from a propeller turbine ?
21. What are tubular or bulb turbines ?
22. What do you mean by 'specific speed' of a turbine ?
23. What is cavitation ? How can it be avoided/checked ?
24. Describe briefly the methods of governing an impulse turbine ?
25. What points should be considered while selecting a right type of turbine ?
26. Enumerate the various controls which are provided in an hydro-electric power plant.
27. Explain the advantages of combined operation of hydro-electric station and thermal station.
28. Compare hydro and thermal power plants.
29. List the advantages and disadvantages of underground power house/station.
30. What safety measures need to be taken for the safe operation of an hydro-electric plant ?
31. What do you mean by 'preventive maintenance' of hydro-plant ?
32. Define hydrology.
33. Draw and explain the hydrologic cycle.
34. Define run-off. How is it measured ?
35. List the factors which affect run-off.
36. What is a hydrograph ?
37. What is a unit hydrograph ? What are the limitations to the use of unit hydrographs ?
38. What is a flow duration curve ?
39. What is a mass curve ?
40. Write a short note on hydropower development in India.

UNSOLVED EXAMPLES

1. The following data is available for a hydro-power plant :
   Available head = 130 m ; catchment area = 2200 sq. km. ; annual average rainfall = 150 cm ; turbine efficiency = 86% ; generator efficiency = 91% , percolation and evaporation losses = 18%.
   Determine power developed in MW taking load factor as unity. [Ans. 8.546 MW]
2. From the investigation of a hydrosite the following data is available :
   Available head = 50 m ; catchment area = 50 sq. km. ; rainfall = 150 cm per year ; 70% of rainfall can be utilized ; turbine efficiency = 80% ; generator efficiency = 91% ; penstock efficiency = 75% ; load factor = 60%.
   Determine the suitable capacity of a turbo-generator.
   [Ans. 750 kW (maximum rating), Francis or Kaplan turbine]

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6

Nuclear Power Plant

6.1. General aspects of nuclear engineering—Atomic structure—Atomic mass unit—Isotopes—Radioactivity—Nuclear radiation—Binding energy—Radioactive decay—Nuclear reactions—Nuclear cross-sections—Fertile materials—Fission of nuclear fuel—Nuclear fusion—Comparison of fission and fusion processes. 6.2. Nuclear power systems. 6.3. Nuclear reactors—Introduction—Classification of nuclear reactors—Essential components of a nuclear reactor—Power of a nuclear reactor—6.4. Main components of a nuclear power plant. 6.5. Description of reactors—Pressurised water reactor (PWR)—Boiling water reactor (BWR)—CANDU (Canadian-Deuterium-Uranium) reactor—Gas cooled reactor—Liquid metal cooled reactors—Breeder reactor. 6.6. Selection of materials for reactor components. 6.7. Advantages and disadvantages of nuclear power plants. 6.8. Nuclear-plant site selection. 6.9. Nuclear power plants in India. Highlights—Theoretical Questions.

6.1. GENERAL ASPECTS OF NUCLEAR ENGINEERING

6.1.1. Atomic Structure

- An element is defined as a substance *which cannot be decomposed into other substances.* The *smallest particle* of an element which takes part in chemical reaction is known as an '*atom*'. The word atom is derived from Greek word 'Atom' which means indivisible and for a long time the atom was considered as such. *Dalton's atomic theory* states that (*i*) all the atoms of one element are precisely alike, have the same mass but differs from the atoms of other elements (*ii*) the chemical combination consists of the union of a small fixed number of atoms of one element with a small fixed number of other elements.
- Various atomic models proposed by scientists over the last few decades are : 1. Thompson's plum puddling model, 2. Rutherford's nuclear model, 3. Bohr's model, 4. Sommerfeld's model, 5. Vector model, 6. Wave-mechanical model.
- The complex structure of atom can be classified into *electrons* and *nucleus*. The nucleus consists of *protons* and *neutrons* both being referred as *nucleons*. *Protons* are *positively* charged and *neutrons* are *neutral*, thus making complete nucleus as positively charged.
- The *electrons* carry *negative* charge and circulate about the nucleus. As the positive charge on proton particle is equal to the negative charge on electron particle, and the *number of electrons is equal to the number of protons,* atom is a neutral element. Any addition of the number of electrons to the neutral atom will make it negatively charged. Similarly any subtraction of the electrons will make it positively charged. Such an atom is known as *ion* and the process of charging the atom is termed an *ionisation*.
- The nuclear power engineering is specially connected with *variation of nucleons in nucleus.* Protons and neutrons are the particles having the mass of about 1837 times and 1839 times the mass of an electron.

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- The modern atomic theory tells that the atom has a diameter of about 10^{-7} mm. In a neutral atom the electrons are bound to the nucleus by the electrostatic forces, which follows the Coloumb's law of forces, *i.e.*, like charges repel and unlike charges attract each other. The function of electrostatic force is similar to the gravitational force.
- The atomic spectrum study has revealed that every electron in an atom is in one group of specific states of motion which is corresponding to its total energy. In an atom the electrons are spinning around the nucleus in orbits. These orbits are called *shells*, which represent the energy levels for the electrons. *All the electrons having very nearly the same total energy are said to be in the same shell.* The shells have been named as *K*, *L*, *M*, *N* etc. Each shell consists of the specific maximum number of electrons. The *K* shell (inner shell) contains **2** electrons, *L* shell has **8** electrons, *M* shell is limited to **18** and the *N* shell possesses **32** electrons. In fact, the number of electrons in any orbit is equal to $2n^2$ where *n* is the serial number of the orbit taking first orbit nearest to the nucleus, *with the exception that the outermost orbit cannot have more than eight electrons* . In a given atom all orbits may not be complete. It is obvious from the study that *amplitude difference in energy between two shells is much more than the difference in between energy levels in one shell.* In a *shell less than the specified number of electrons may exist but not a large number.* The inner shell is filled up first and then the other successive shells are completed.
- The *chemical properties of the atom varies with composition of number of electrons in various shells and the state of energies within the shells determine the electrical characteristics of the atom.* For example, *Hydrogen* (H_2) consists of one electron in the *first shell*, *Helium* (He) has two electrons in the first shell, *Lithium* (Li) has two electrons in first shell and one is second shell, *Carbon* (C) consists of two electrons in first and four in second shell.

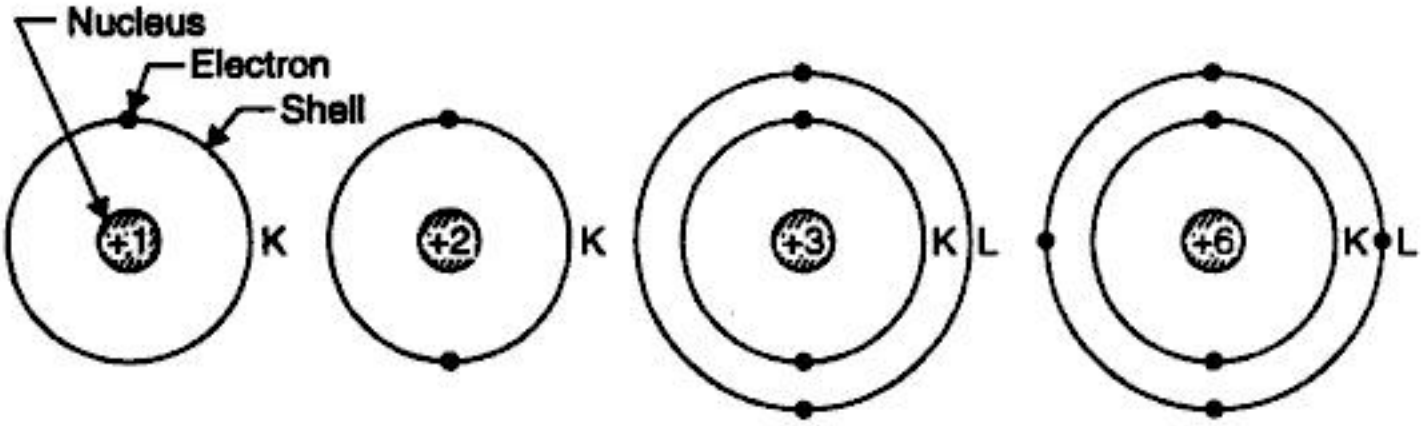

Fig. 6.1 (*a*). Atomic structure of H_2, He, Li and C.

- The electrons lying in the outermost shell are termed *valence electrons.* If the outermost shell is completely filled, the atom is stable and will not take any electron to fill up the gap. However, the incomplete outer shell will try to *snatch* the required number of electrons from the adjacent atom in a matter. The binding force between the electron and nucleus is the electrostatic force of attraction. *To emit one electron energy required is more than the electrostatic force of attraction. When the energy is supplied, the electron jumps from one discrete energy level to another permissible level. The process starts from outer shell.* The electron possesses the energy in two forms, *i.e.*, kinetic energy due to its motion and potential energy due to its position with respect to the nucleus. It is obvious that *electrons cannot exist in between the permissible orbits.*
- The charge of nucleus is represented by the *number of protons* present. This number is known as *atomic number* and designated by the letter *Z*. It also shows the position of atom in the periodic table. Hydrogen has only one number but natural uranium has ninety two. The atoms having *higher atomic number* have been developed artificially ranging from

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93 to 102. These are einsteinium (Z = 99), Ferinium (Z = 100), and mendelevium (Z = 101). Platonium (Z = 94) is an important element to the nuclear power field.

The *mass number* (A) is the sum of total number of protons and neutrons in a nucleus. The number of electrons is represented by the letter N, *i.e.*, $N = (A - Z)$.

6.1.2. Atomic Mass Unit

The *mass of the atom is expressed in terms of the mass of the electron.* The unit of mass has been considered as $\frac{1}{16}$ th of the mass of neutral oxygen atom which contains 8 protons and 8 neutrons. The atomic mass unit (a.m.u.) is equal to $\frac{1}{16}$ th the mass of oxygen neutral atom.

One a.m.u. = 1.66×10^{-24} g

$$\text{Mass of proton} = 1837 \text{ me} = \frac{1837 \times 9.1 \times 10^{-28}}{1.66 \times 10^{-24}} = 1.00758 \text{ a.m.u.}$$

$$\text{Mass of neutron} = 1839 \text{ me} = \frac{1839 \times 9.1 \times 10^{-28}}{1.66 \times 10^{-24}} = 1.00893 \text{ a.m.u.}$$

It has been concluded that the density of matter in a nucleus is enormous. It has been investigated that the *radius of nucleus is equal* to $1.57 \times 10^{-3} \times 3\sqrt{A}$, where A is the number of nucleons in nucleus.

The density of uranium by calculations comes to 1.65×10^{14} g/cm^3. It has been found by calculations that *natural substance has density millions of times lower than that of nuclear matter.*

Electron volt. The energy is expressed in electron volt unit. An electron volt is equal to *work done in moving an electron by a potential difference of one volt.* Or *it is the amount of energy acquired by any particle with one electronic charge, when it falls through a potential of one volt.*

One electron volt = 1.602×10^{-19} joule.

6.1.3. Isotopes

In any atom, the *number of electrons is equal to number of protons.* This is independent of neutrons in the nucleus. *Atoms having different number of neutrons than the number of protons are known as 'Isotopes.'*

Example. Isotopes of hydrogen are shown below [Fig. 6.1 (*b*)].

H_1 – Hydrogen (No neutron) | H_2 – Heavy hydrogen or Deuterium – D | H_3 – Heavy hydrogen or Tritium – T

Fig. 6.1 (*b*).

These isotopes have the *same chemical properties* and *have the same atomic number* and *occupy the same place in the periodic table.* But the *nuclear properties* of each of the isotopes are different *because of the different number of neutrons in the nucleus.*

The isotopes of oxygen vary from O_{14} to O_{19}. The change of number of neutrons in nucleus affect the mass of atom.

Example. Weight of heavy hydrogen is twice the weight of simple hydrogen. This means a volume of H_2O weighs less than the same volume of D_2O.

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Reaction neutrons. These are the neutrons ejected from a nucleus by interaction with one of several particles. There are known cases of neutron emission resulting from a nucleus interacting with a neutron, proton, or alpha particle. Important use is made of this process in producing neutron sources for reactor start-up.

3. Protons :

Protons are produced in a few radioactive-decay processes and more frequently by neutron-proton reactions in which an incident neutron causes a proton to be emitted from the nucleus.

4. Alpha particles :

Alpha particles are produced by the decay of several fission products and a few activated materials as well as by a few neutron-alpha reactions in which an incident neutron interacts with and causes an alpha particle to be emitted from the nucleus.

5. Beta particles :

Beta particles (electrons and positrons) are produced by several mechanisms, such as radioactive decay and pair production (in which a photon of high energy is converted into an electron-positron pair).

Effects of nuclear radiation on matter :

Nuclear radiation, when it interacts with any material, deposits energy in the material and can have various effects. In chemical components the chemical form will be changed, in solids the crystalline structure may be altered, in any case heat will be generated. For charged particles and gamma rays the mechanisms of energy transfer is ionisation of the material traversed by the radiation. Ionization is the production of electrically charged particles by stripping orbital electrons from the electrically neutral atoms. In the case of neutrons, the primary energy-transfer process is a kinetic-energy exchange caused by collision of neutrons with nuclei of the matter traversed.

6.1.6. Binding Energy

The nucleus of an atom is formed when the nucleons come closer to each other and this distance between the two nucleons is of the order of nearly 10^{-12} mm. At the *moment of combination there is a release of energy* and is known as *'binding energy'*. Further if it is required to separate out or to disintegrate two nucleons the equivalent amount of binding energy is to be supplied from the external source to overcome the force of attraction. The binding energy can also be defined as the *energy required to overcome the binding forces of nucleus.*

When two nuclear particles are combined to form a nucleus, it is observed that, there is a difference in the mass of the resultant nucleus and the sum of the masses of two parent nuclear particles. This decrement of mass is known as *'mass defect'*. The *amount of mass defect is directly proportional to the amount of energy released.*

The nuclear binding energy per nucleon increases with the increase of the number of nucleons in the nucleus. *Example* : The binding energy per nucleon for H^2 is 1.109 MeV and for He^4 it is $28.2 + 4 \simeq 7.05$ MeV. A curve representing the variation of nuclear binding energy per nucleon with the mass number is shown in Fig. 6.2. Here the average value of binding energy per nucleon has been considered. The curve indicates that the average binding energy per nucleon increases as the mass number increases initially with the peak value of about 8.8 MeV at nearly 60 mass number. The elements falling in this region are nickel and iron. As the mass number increases still further, the binding energy curve falls gradually to 7.6 MeV for U^{238}. For U^{235} from the Fig. 6.2 the binding energy per nucleon is 7.7 MeV. At the point where mass number is 117, binding energy per nucleon is nearly 8.6 MeV.

U^{235} nucleus is splitted into two approximately equal nuclei. The formation of two nuclei will release the energy of about 0.9 MeV per nucleon. There is a release of energy as the mass number

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decreases within the range of 60 to 250 mass number. This release of energy is corresponding to the increase of mass defect. In fission process, the U^{235} nuclei is splitted to two other nuclei and energy is liberated.

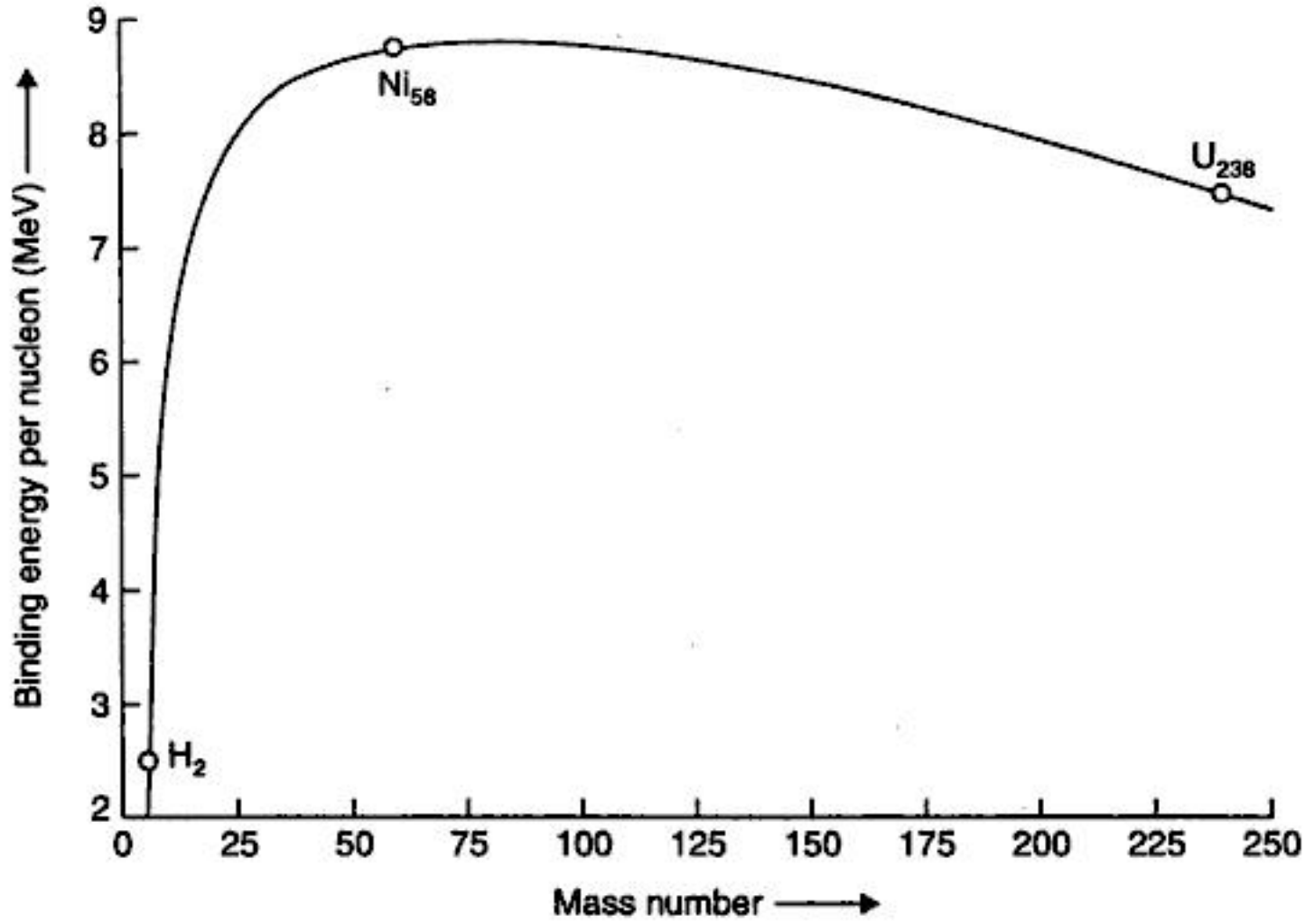

Fig. 6.2. Variation of average binding energy per nucleon with mass number.

It is evident from the above discussion that the nuclear transformations of other nucleus is also possible such as U^{235}, U^{233} and Pu^{239} (these are the important fuels used in the production of nuclear power).

An atom with even number of protons of mass number is more stable because of the pairing of protons and neutrons. This type of atom also possesses *higher binding energy per nucleon* and is represented as *even type of atom*. In nuclear physics, the first even or odd represents the even or odd number of protons respectively and second one represents the even or odd mass number. This is obvious from the practical data that the U^{235} is fissionable with slow neutrons (neutrons having less energy) but U^{238} is fissionable only when the neutrons are having energy more than 1 MeV.

6.1.7. Radioactive Decay

It has been observed that the emission of the particles in the form of alpha, beta or gamma radiations is not an instantaneous process. For various elements the decay time is different, which follows a certain *law*. Obviously the process is independent of the physical and chemical properties of the given isotope at a particular temperature and pressure.

The *law* states that the *small amount of disintegration of the isotope in a small period is directly proportional to the total number of radioactive nuclei and proportionality constant.*

If, N = Number of radioactive nuclei present at any time t,

N_0 = Initial number of such nuclei,

λ = Proportionality constant (also known as disintegration constant or the radioactive decay constant of the material),

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Then the above law can be stated in the form of equation as follows :

$$\Delta N = -\lambda N \Delta t \qquad ...(6.1)$$

or,
$$\frac{dN}{dt} = -\lambda N \qquad ...(6.2)$$

The *negative* sign represents that during disintegration the number of the nuclei is *decreasing*.

Integrating the above equation (6.2) after proper arrangement within the proper limits, we get

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt \qquad ...(6.3)$$

or, $\log_e N - \log_e N_0 = -\lambda t$, or, $\log_e \frac{N}{N_0} = -\lambda t$

or, $\frac{N}{N_0} = e^{-\lambda t}$, or, $N = N_0 e^{-\lambda t}$ ...(6.4)

$$\frac{dN}{dt} = -\lambda N = -\lambda N_0 e^{-\lambda t} \qquad ...(6.5)$$

The eqn. (6.5) represents that the *decay scheme follows the exponential law.*

Activity :

The intensity of emitted radiation is termed **activity.**

This is directly dependent on the rate of disintegration of the element.

If, A = Activity at time t,

A_1 = Initial activity,

k = Detection coefficient,

Then, $$A = k\left(-\frac{dN}{dt}\right) = k\lambda N = k\lambda N_0 e^{-\lambda t} = A_1 e^{-\lambda t} \qquad ...(6.6)$$

Half-life :

***Half-life** represents the rate of decay of the radioactive isotopes.* The half-life is the *time required for half of the parent nuclei to decay or to disintegrate.*

Putting $N = \frac{N_0}{2}$ and $t = t_{1/2}$ in eqn. (6.5), we get

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \quad \therefore \quad e^{-\lambda t_{1/2}} = 1/2$$

$$\therefore \quad \lambda t_{1/2} = \log_e 2 = 0.693 \quad \therefore \quad t_{1/2} = \frac{0.693}{\lambda} \qquad ...(6.7)$$

Here $t_{1/2}$ is the half-life of radioactive nuclei. After passing every half-life the number of nuclei is reduced to half and so is the activity. This process is repeated for the several half lives till the activity becomes negligible. The variation of half-life is from fraction of seconds to million of years.

Half-life of some of the metals is given below :

Metal	*Half-life*
Po-214	170 μ sec
I-137	25 sec
Carbon-14	5100 years
Th-232	1.4×10^{10} years
Uranium-238	4.525×10^{9} years

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Average (mean) life :

This indicates the average of total time for which the radioactive nuclei has disintegrated for several half lives. Hence this is *greater than half-life.* This is obtained by taking the sum of the decay time of the radioactive nuclei and then it is divided by the initial number of nuclei.

If T is the time of average life, then

$$T = \frac{-\int_0^\infty t\,dN}{N_0} = \frac{\lambda N_0 \int_0^\infty t e^{-\lambda t}\,dt}{N_0} \qquad ...(6.8)$$

Now integrating by parts, we get

$$T = \left[-te^{-\lambda t} - \frac{e^{-\lambda t}}{\lambda}\right]_0^\infty = \frac{1}{\lambda} \qquad ...(6.9)$$

But, $$t_{1/2} = \frac{0.693}{\lambda}$$

From the above eqns. it is clear that mean life is 1.445 times greater than half-life.

Note. Number of disintegrations per second is the unit of radioactivity and is termed *curie*, as this phenomenon was first discovered by Curie.

6.1.8. Nuclear Reactions

During a nuclear reaction, the *change in the mass of the particle represents the release or an absorption of energy.* If the total mass of the particle after the reaction is reduced, the process releases the energy, consequently, the increase in the mass of the resultant particle, will cause the absorption of energy.

The equations of nuclear reactions are connected with the resettlement of protons and neutrons within the atom. The equations are much similar to chemical reactions. The energy variation is also of the order of MeV. In simple term the equation shows the *balance of neutron and proton.*

A nuclear reaction is written as follows :

(*i*) The bombarded nuclei or the target nuclei is written first from left hand side.

(*ii*) In the middle within brackets, first is the incident particle and second one the ejected.

(*iii*) On the right hand side, the resultant nucleus is placed.

A *neutron* is written as : ${}_0n^1$ because it has unit mass and it does not have any charge.

An *electron* is written as : ${}_{-1}e^0$ because its mass is negligible as compared to proton or neutron and its charge is equal but opposite to the charge of proton.

Some of the *examples of reactions* are given below :

(*i*) When ${}_{11}Na^{23}$ is bombarded with protons possessing high energy, it is converted to ${}_{12}Mg^{23}$

$${}_{11}Na^{23} + {}_1H^1 \longrightarrow {}_{12}Mg^{23} + {}_0n^1 + q \qquad ...(6.10)$$

(where q = release or absorption of energy in the reaction)

(*ii*) When ${}_{13}Al^{27}$ is bombarded with high energy protons it is transformed to ${}_{14}Si^{27}$.

$${}_{13}Al^{27} + {}_1H^1 \longrightarrow {}_{14}Si^{27} + {}_0n^1 + q \qquad ...(6.11)$$

(*iii*) When ${}_{13}Al^{27}$ is bombarded with deutrons, Al^{28} and proton may be produced.

$${}_{13}Al^{27} + {}_1H^2 \longrightarrow {}_{13}Al^{28} + {}_1H^1 \qquad ...(6.12)$$

The eqns. (6.10), (6.11) and (6.12) may be written in the equation form as given below :

$$Na^{23}(p, n)Mg^{23} \qquad ...(6.13)$$

$${}_{13}Al^{27}(p, n)Si^{27} \qquad ...(6.14)$$

$$Al^{27}(d, p)Al^{28} \qquad ...(6.15)$$

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It is evident from the above mentioned reactions that the *nuclear reaction is followed by capturing a particle, resulting in a compound excited nucleus, which undergoes further transformation in a short period of time.*

The *transformation may adopt the following five main different paths :*

1. Elastic scattering. The neutron interacts with the nucleus and after transformation the compound nucleus emits a particle which is identical to the captured one. There is also no change in the resultant nucleus. The *total internal energy* of the bombarded nucleus and the restriking particle *will not change* at all. The process is known as *elastic scattering*. Elastic scattering is also termed as *elastic collision*. When the neutron strikes the nucleus, it imparts the part of initial kinetic energy and momentum to the nucleus which causes the displacement of the nucleus in the crystal lattice by a significant distance and can *change the structural properties of the material.*

In elastic scattering process the *kinetic energy of neutron is reduced and is beneficial to slow down the neutron in reactor.* In this transformation, *there is neither release nor absorption of energy but as a result of collision, redistribution of kinetic energy takes place.*

Example of elastic scattering. When a neutron strikes a light nucleus (*e.g.*, hydrogen nucleus), the velocity of the neutron is very much reduced and the energy is transferred to the proton. Here most of the energy is transferred because both the particles are having nearly the *same masses*. It has been observed that in such a single collision, the loss of energy of the proton is nearly 70 to 75 percent. In case the neutron impacts with the heavy nucleus, the energy loss in single collision is *less*. With carbon nucleus this loss amounts to nearly 12 to 17 percent of the initial value. The reaction is written as $C^{12}(n, n)C^{12}$.

2. Inelastic scattering. The composition of the incident particle and ejected particle remains unchanged. When the particle interacts with the nuclei it loses its kinetic energy and the target nucleus is excited. The energy is released in the form of gamma emission. This transformation is known as *inelastic scattering* or collision. The process is limited to the condition that the neutron should have minimum energy sufficient to excite the target nucleus. The reaction is completed with the absorption or release of energy. The neutron energy loss is of the order of 10 to 20 percent of the initial value.

When a fast moving neutron hits the U^{238} nucleus, the nucleus is excited and there is an emission of gamma quantum [U^{238} (n, $\eta\gamma$) U^{238}].

3. Capture. In this process the incident particle may be captured or absorbed by the nucleus and may raise the mass number by unity. The nucleus is excited and the energy is emitted in the form of gamma quantum. The *artificial radioactive materials are produced by this process.* In a reactor, Co-60 isotope is produced by bombarding the natural Co-59 with neutrons. The reaction has both the possibilities of producing the stable and unstable nucleus and may result in (n, γ) or (p, γ) reactions. This transformation may take place with elastic scattering. When a neutron interacts with light hydrogen, it forms heavy hydrogen, deuterium. The mass of deuterium is less than its components. This mass defect is corresponding to the release of gamma quantum.

4. In this reaction, the *impinging particle is trapped in the nucleus but the ejected particle is a different one. The composition of the resultant nucleus is also different from the parent nucleus.*

5. Fission. *When the nucleus is excited too much, it splits into two mostly equal masses.* This particular reaction is suited only to the *heavy nucleus* such as U^{233}, U^{235}, Pu^{239} etc. The transformation is known as *fission*. The produced two nuclei are lighter nuclei ; they have *more binding energies per nucleon and hence this reaction always releases the energy* (Fig. 6.2).

6.1.9. Nuclear Cross-sections

Cross-sections (or attenuation coefficients) *are measures of the probability that a given reaction will take place between a nucleus or nuclei and incident radiation.*

Cross-sections are called either *microscopic* or *macroscopic*, depending on whether the reference is to a single nucleus or to the nuclei contained in a unit volume of material.

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Microscopic cross-section :

It is a measure of the probability that a given reaction will take place between a single nucleus and an incident particle. Microscopic cross-section is usually denoted by the symbol σ and is expressed in terms of the *effective area that a single nucleus presents for the specified reaction*. Since these cross sections are usually quite small, in the range of 10^{-22} to 10^{-26} cm^2/nucleus it is general practice to express them in terms of a unit called the *barn*, which is 10^{-24} cm^2/nucleus.

Macroscopic cross-sections :

These are the products of microscopic cross-sections and the atomic density in nuclei per cubic centimeter and are equivalent to the total cross-section, for a specific reaction of all the nuclei in 1 cm^3 of material. Macroscopic cross-sections are denoted by the symbol Σ for *neutrons* and μ for *gamma rays* and have the units cm^{-1}.

Gamma ray cross-sections :

Although there are a large number of interaction processes that take place between gamma rays and matter, the most commonly used are the energy-absorption cross-section (used to determine gamma heating and dose rates) and the total attenuation cross-section (used to determine material gamma-ray attenuation and for shielding design).

Neutron cross-sections :

Neutrons undergo a large number of different interaction processes with matter, and, unlike gamma rays, many of these individual interactions must be evaluated. Neutron cross-sections of general use are :

(*i*) Fission
(*ii*) Gamma-ray production
(*iii*) Activation
(*iv*) Elastic scattering
(*v*) Inelastic scattering
(*vi*) Reaction particle production
(*vii*) Total absorption
(*viii*) Total attenuation.

Both neutron and gamma-ray cross-sections are *energy-dependent properties*. Plots of gamma-ray cross-section *vs* photon energy for all materials are, over the energy range of interest, *smooth curves*, whereas for neutron cross sections the curves of many materials *show gross variations from a smooth curve*. The variations in neutron cross-sections show up as peaks and valleys on the cross-section plot ; these peaks are called *resonances*. When a material has a large number of resonance peaks over a portion of the energy range, this portion of the cross-section plot is called a *resonance region*. The *resonance region can have a significant effect on reactor design*, since the material U^{238} which is present in most fuels has a relatively wide resonance region which can cause extensive neutron absorption during the slowing down of neutrons to thermal energy.

The known cross-sections for materials potentially useful in reactor systems are used as primary criteria in materials selection. For example, high-neutron-absorption cross-section materials would not normally be used as materials of construction in the vicinity of a reactor core to prevent competition for the neutrons required to sustain the fission process ; and high activation cross-section materials would not be chosen, if they can be avoided, in a region exposed to a high neutron flux during operation, if that region is to be accessible after reactor shut-down.

6.1.10. Fertile Materials

It has been found that some materials are not fissionable by themselves but they *can be converted to the fissionable materials*, these are known as *fertile materials*.

Pu^{239} and U^{233} are not found in nature but U^{238} and Th^{232} can produce them by nuclear reactions. When U^{238} is bombarded with slow neutrons it produces $_{92}U^{239}$ with half-life of 23.5 days which is unstable and undergoes two beta disintegratio.. The resultant Pu^{239} has half-life of 2.44×10^4 yrs and is a good alpha emitter.

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$$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \gamma \quad \text{...(6.16)}$$

$$_{92}U^{239} \xrightarrow{23.5 \text{ min.}} -{}_{-1}e^{0} + {}_{91}Np^{231} \quad \text{...(6.17)}$$

$$_{93}Np^{239} \xrightarrow{2.3 \text{ days}} {}_{-1}e^{0} + {}_{94}Pu^{239} \quad \text{...(6.18)}$$

During conversion the above noted reactions will take place. The other isotopes of neptunium such as 2.1 day Np^{238} and plutonium can also be produced by the bombardment of heavy particles accelerated by the cyclotron.

The nuclear transformations to convert $_{90}Th^{232}$ to U^{233} are given below :

$$_{90}Th^{232} + {}_{0}n^{1} \longrightarrow {}_{90}Th^{233} + \gamma \quad \text{...(6.19)}$$

$$_{90}Th^{233} \xrightarrow{23.3 \text{ min.}} {}_{91}Pa^{233} + {}_{-1}e^{0} \quad \text{...(6.20)}$$

$$_{91}Pu^{233} \xrightarrow{27.4 \text{ days}} {}_{92}U^{233} + {}_{-1}e^{0} \quad \text{...(6.21)}$$

U^{235} is the source of neutrons required to derive Pu^{239} and U^{233} from Th^{232} and U^{238} respectively. This process of conversion is performed in the *breeder reactors*.

Other fissionable materials. Th^{227}, Pa^{232}, U^{231}, Np^{238} and Pu^{241} are the other nuclides which are having high cross-sections for neutron thermal fission. Pu^{241} is the important nuclide which is used in plutonium fueled power reactors.

6.1.11. Fission of Nuclear Fuel

Fission *is the process that occurs when a neutron collides with the nucleus of certain of the heavy atoms, causing the original nucleus to split into two or more unequal fragments which carry off most of the energy of fission as kinetic energy*. This process is *accompanied by the emission of neutron and gamma rays*.

Fig. 6.3 is a representation of the fission of uranium 235. The *energy released as a result of fission is the basis for nuclear-power generation*. The release of about *2.5 neutrons / fission* makes it possible to produce *sustained fissioning*.

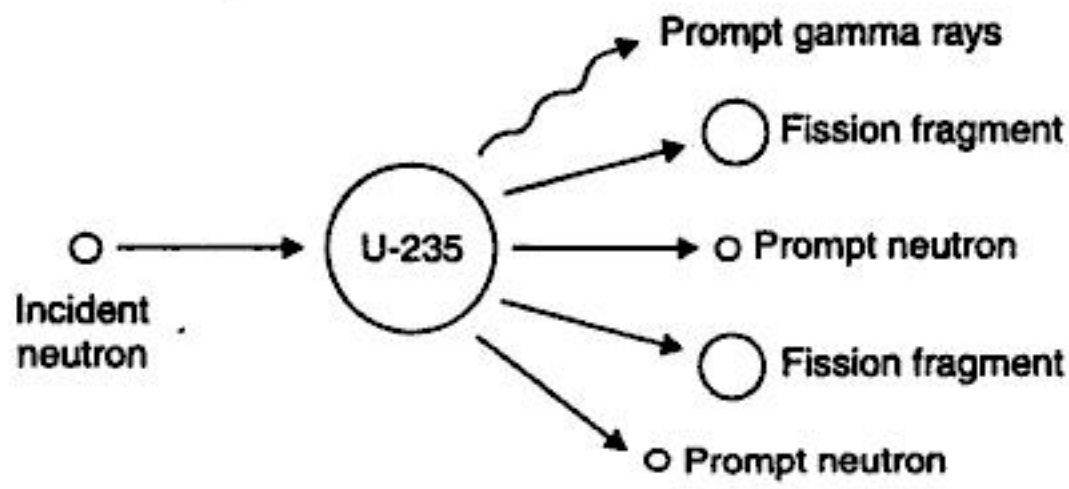

Fig. 6.3. Fission of uranium 235. Incident neutron, upon colliding with U^{235} nucleus, causes fission to take place, resulting in the production of fission fragments, prompt neutrons and prompt gamma rays.

The *fission fragments* that result from the fission process are *radioactive* and decay by emission of beta particles, gamma rays and to a lesser extent alpha particles and neutrons. The neutrons that are emitted after fission, by decay of some of the fission fragments, are called *delayed neutrons*. These are of the utmost importance, since *they permit the fission chain reaction to be easily controlled*.

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The total detectable *energy released* owing to the fission of a single nucleus of uranium 235 is 193 MeV, distributed as shown below :

Distribution of fission energy

	MeV
Instantaneous energy release :	
Kinetic energy of fission fragments	168
Prompt-gamma-ray energy	7
Kinetic energy of prompt neutrons	5
Instantaneous total	180
Delayed energy release :	
Beta particle decay of fission products	7
Gamma-ray decay of fission products	6
Delayed total	13

As is shown above, the neutron emitted as a result of fission of a uranium 235 nucleus carry off 5 MeV of kinetic energy. Since on average there are about 2.5 neutrons emitted/U^{235} fission, the average neutron energy is 2 MeV. Actually fission neutrons are emitted with an energy speed of from nearly zero energy to approximately 16 MeV, the bulk of the them being in the 1- to 2-MeV energy region.

Note. Although not strictly a result of the fission process, there is an additional 5 to 8 MeV emitted per fission as a result of the capture of neutrons not used in the fission chain reaction. About 1 MeV of this total is emitted over a period of time owing to decay of activation products, and the remainder is emitted immediately upon neutron capture.

Most of the reactors in existence today or planned for the near future are called *thermal reactors*, since they depend on neutrons which are in or near thermal equilibrium with their surroundings to cause the bulk of fissions. *These reactors make use of the fact that the probability for fission is highest at low energy by slowing down the neutrons emitted as a result of fissioning to enhance fission captures in the fuel.* Loss of neutrons to non-fission-capture processes is lessened by minimising the quantity of non-fissile material in or near the reactor core. *The materials used to decelerate fast neutrons to thermal energy levels* are called **moderators.** Effective and efficient moderators must slow the fission neutrons, in the 1- to 2-MeV range to thermal energy at about 0.025 eV to less than 0.1 eV. This effect must be produced in a small volume and with very little absorption.

The Chain reaction :

A chain reaction is that process in which the number of neutrons keeps on multiplying rapidly (in geometrical progression) during fission till whole of the fissionable material is disintegrated. The chain reaction will become self-sustaining or self propagating only if, for every neutron absorbed, at least one fission neutron becomes available for causing fission of another nucleus. This condition can be conveniently expressed in the form of *multiplication factor or reproduction factor* of the system which may be definded as

$$K = \frac{\text{No. of neutrons in any particular generation}}{\text{No. of neutrons in the preceding generation}}$$

If $K > 1$, chain reaction will continue and if $K < 1$, chain reaction cannot be maintained.

Fig. 6.4 shows schematically a chain reaction which when set off ultimately leads to a rapidly growing avalanche having the characteristic of an explosion. The rate of growth of the chain process is shown in Fig. 6.5.

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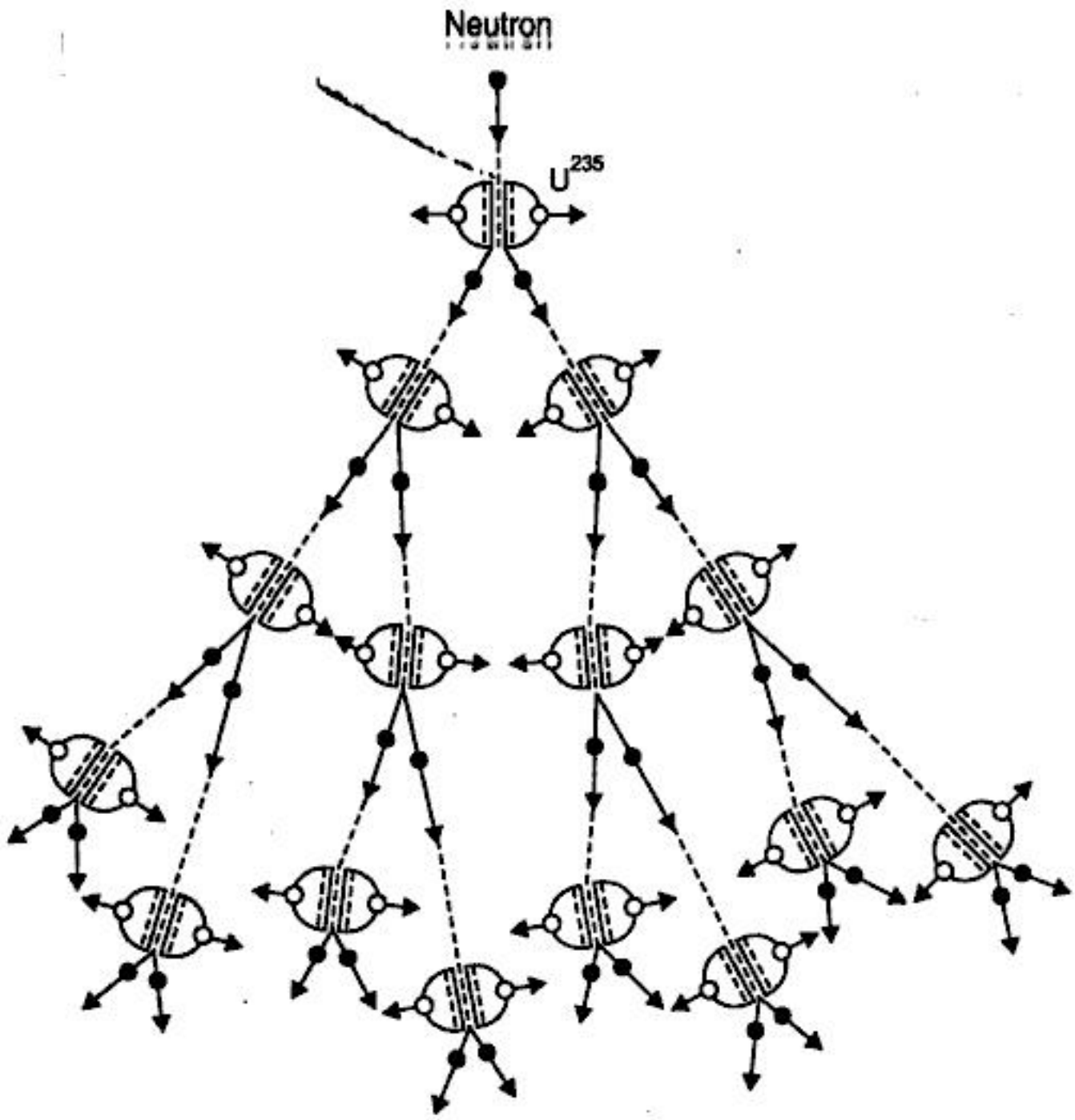

Fig. 6.4. Chain reaction.

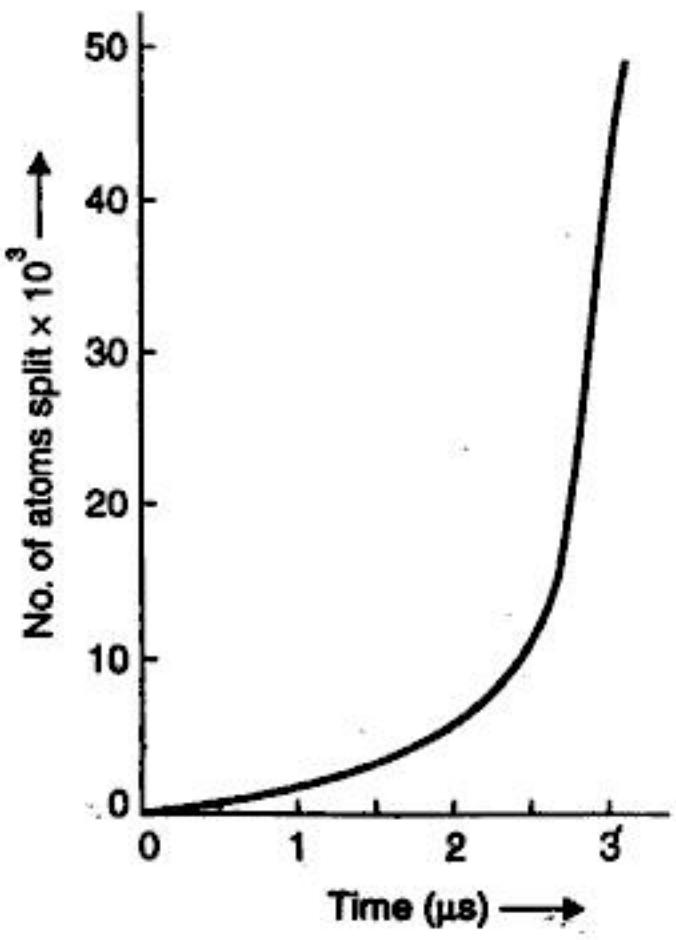

Fig. 6.5. The rate of growth of the chain process.

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Among the nuclear radiations produced in a reactor the alpha and beta particles, thermal (slow) neutrons, fast neutrons and gamma rays are harmful ones and must be shielded against. Of these only the fast neutrons and gamma rays present some serious difficulty in designing the reactor shielding, since alpha and beta particles can be stopped by a fraction of an inch of a solid substance, while thermal neutrons can be automatically guarded against with a shield thick enough to provide protection against fast neutrons and gamma rays.

The effectiveness of a nuclear shield against gamma rays approximately depends upon its mass. A heavy material like lead will be a more effective shield per unit weight, than a light element such as carbon. On the other hand, light elements, particularly hydrogen are much more effective per unit weight than heavy elements for fast neutron shielding. Concrete is a material that offers a compromise between these two extreme characteristics of shielding material for *both gamma rays and fast neutrons*. It is a material which has *low cost* and is *easily available*.

The actual design of the shield, however, involves the following *considerations :*

(*i*) The total amount of radiation produced in the reactor.

(*ii*) The amount of radiation that can be permitted to leak through the shield.

(*iii*) The shielding properties of material.

6.3.4. Power of a Nuclear Reactor

The fission rate of a reactor *i.e.*, total number of nuclei undergoing fission per second in a reactor is

$$= nC\sigma NV = \phi_{nu}\, \sigma NV$$

where, n = Average neutron density *i.e.*, number per m^3,

C = Average speed in m/s,

$\phi_{nu} = nC$ = Average neutron flux,

N = Number of fissile nuclei /m^3,

σ = Fission cross-section in m^2, and

V = Volume of the nuclear fuel.

Since 3.1×10^{10} fission per second generate a power of one watt, the power P of a nuclear reactor is given by,

$$P = \frac{nC\sigma NV}{3.1 \times 10^{10}} \text{ watt}$$

$$= 3.2 \times 10^{-11}\, nC\sigma\, NV \text{ watt}$$

$$= 3.2 \times 10^{-11}\, \phi_{nu}\, \sigma\, NV \text{ watt}$$

Now, NV = Total number of fissile nuclei in the reactor fuel

$$= m \times 6.02 \times 10^{26}/235$$

where, m is the mass of the U^{235} fuel. It is known that fission cross-section σ of U^{235} for thermal neutrons is 582 barns = 582×10^{-28} m^2.

$$\therefore \quad P = \frac{3.2 \times 10^{-11} \times \phi_{nu} \times 582 \times 10^{-28} \times m \times 6.02 \times 10^{26}}{235}$$

$$= 4.77 \times 10^{-12}\, m\, \phi_{nu} \text{ watt}$$

$$\simeq 4.8 \times 10^{-12}\, mnC \text{ watt.}$$

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6.4. MAIN COMPONENTS OF A NUCLEAR POWER PLANT

Fig. 6.11 shows schematically a nuclear power plant.

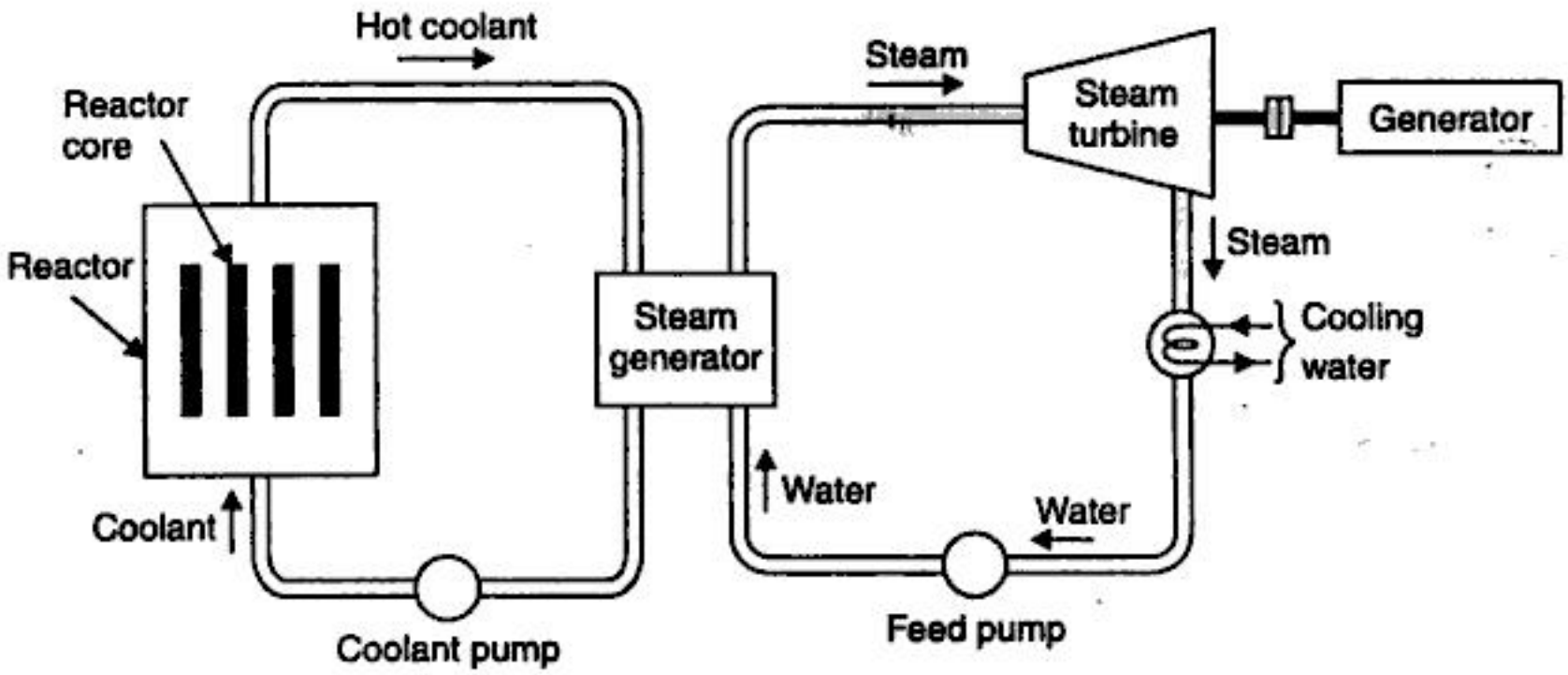

Fig. 6.11. Nuclear power plant.

The *main components of a nuclear power plant* are :

1. Nuclear reactor
2. Heat exchanger (steam generator)
3. Steam turbine
4. Condenser
5. Electric generator.

In a nuclear power plant the reactor performs the same function as that of the furnace of steam power plant (*i.e.*, produces heat). The heat liberated in the reactor as a result of the nuclear fission of the fuel is taken up by the coolant circulating through the reactor core. Hot coolant leaves the reactor at the top and then flows through the tubes of steam generator and passes on its heat to the feed water. The steam so produced expands in the steam turbine, producing work and thereafter is condensed in the condenser. The steam turbine in turn runs an electric generator thereby producing electrical energy. In order to maintain the flow of coolant, condensate and feed water pumps are provided as shown in Fig. 6.11.

6.5. DESCRIPTION OF REACTORS

6.5.1. Pressurised Water Reactor (PWR)

A pressurised water reactor, in its simplest form, is a light water-cooled and moderated thermal reactor having an unusual core design, using both natural and highly enriched fuel. The principal parts of the reactor are :

1. Pressure vessel
2. Reactor thermal shield
3. Fuel elements
4. Control rods
5. Reactor containment
6. Reactor pressuriser.

The components of the secondary system of pressurised water plant are similar to those in a normal steam station.

Refer to Fig. 6.12. In PWR, there are two circuits of water, one *primary circuit* which passes through the fuel core and is *radioactive*. This primary circuit then produces steam in a *secondary circuit* which consists of heat exchanger or the boiler and the turbine. As such the steam in the

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turbine is *not radioactive* and need not be shielded. The *pressure* in the primary circuit should be *high* so that the boiling of water takes place at high pressure. A *pressuring tank* keeps the water at about 100 kgf/cm^2 *so that it will not boil*. Electric heating coils in the pressuriser boil some of the water to form steam that collects in the dome. As more steam is forced into the dome by boiling, its pressure rises and pressurises the entire circuit. The pressure may be reduced by providing cooling coils or spraying water on the steam.

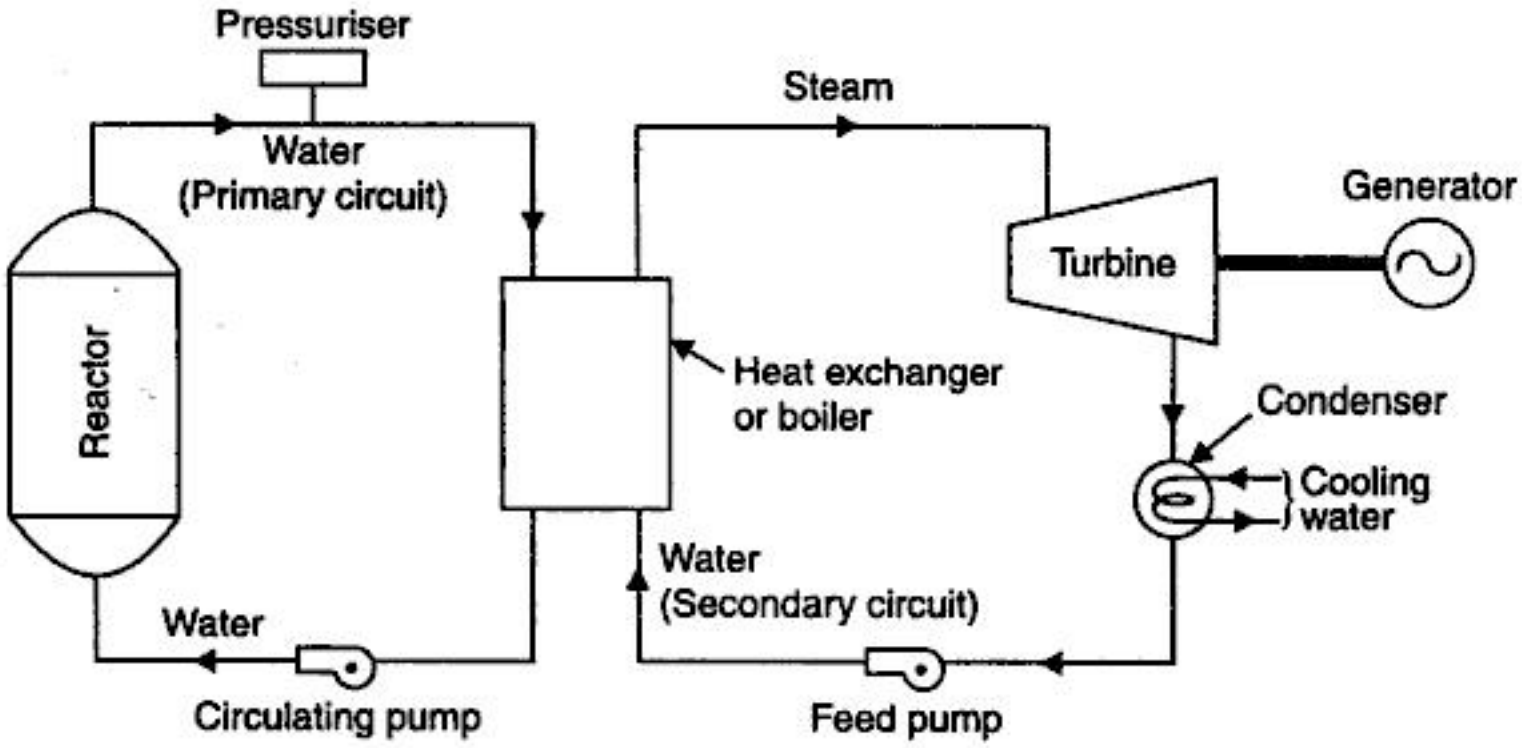

Fig. 6.12. Pressurised water reactor.

Water acts both as coolant as well as moderator. Either heavy water or the light water may be used for the above purpose.

A pressurised water reactor *can produce only saturated steam*. By providing a separate furnace, the steam formed from the reactor could be superheated.

Advantages of PWR :

1. Water used in reactor (as coolant, moderator and reflector) is cheap and easily available.
2. The reactor is compact and power density is high.
3. Fission products remain contained in the reactor and are not circulated.
4. A small number of control rods is required.
5. There is a complete freedom to inspect and maintain the turbine, feed heaters and condenser during operation.
6. This reactor allows to reduce the fuel cost extracting more energy per unit weight of fuel as it is ideally suited to the utilisation of fuel designed for higher burn-ups.

Disadvantages :

1. Capital cost is high as high primary circuit requires strong pressure vessel.
2. In the secondary circuit the thermodynamic efficiency of this plant is quite low.
3. Fuel suffers radiation damage and, therefore its reprocessing is difficult.
4. Severe corrosion problems.
5. It is imperative to shut down the reactor for fuel charging which requires a couple of month's time.
6. Low volume ratio of moderator to fuel makes fuel element design and insertion of control rods difficult.
7. Fuel element fabrication is expensive.

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6.5.2. Boiling Water Reactor (BWR)

In a boiling water reactor *enriched fuel* is used. As compared to PWR, the arrangement of BWR plant is simple. The plant can be safely operated using natural convection within the core or forced circulation as shown in the Fig. 6.13. For the safe operation of the reactor the pressure in the forced circulation must be maintained constant irrespective of the load. In case of *part load operation of the turbine some steam is by-passed.*

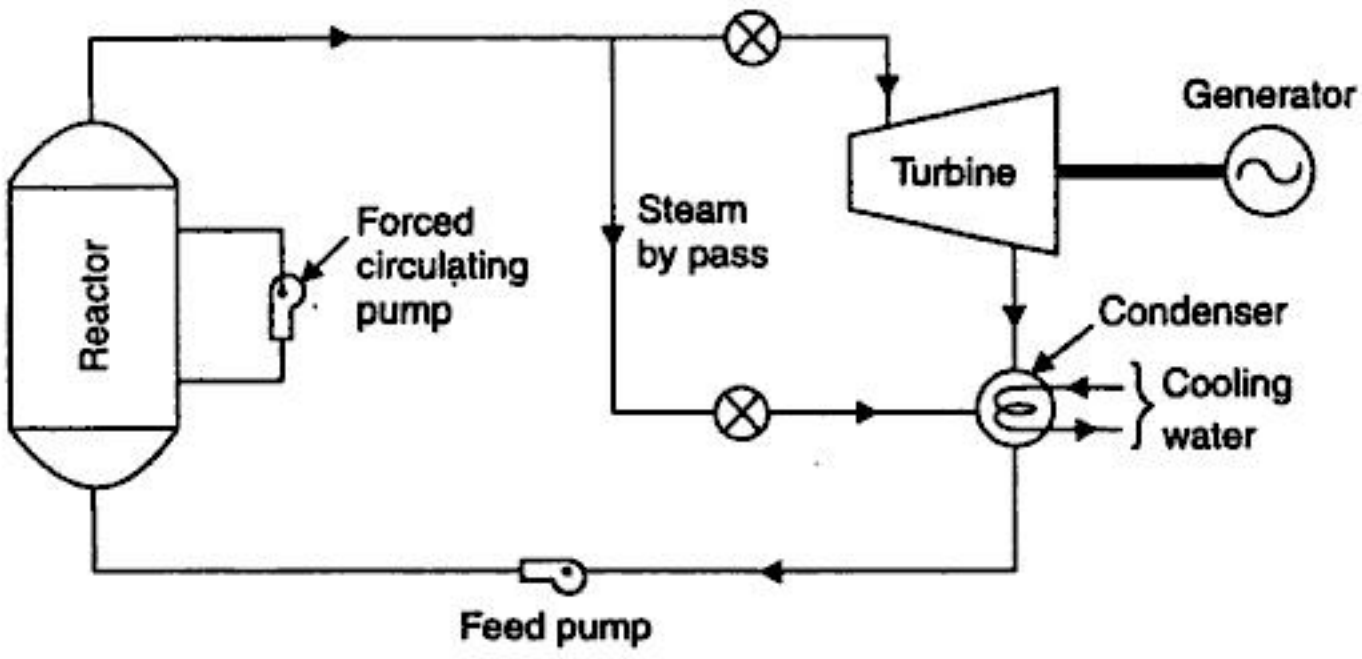

Fig. 6.13. Boiling water reactor.

Advantages of BWR :

1. Heat exchanger circuit is eliminated and consequently there is gain in thermal efficiency and gain in cost.
2. There is use of a lower pressure vessel for the reactor which further reduces cost and simplifies containment problems.
3. The metal temperature remains low for given output conditions.
4. The cycle for BWR is more efficient than PWR for given containment pressure, the outlet temperature of steam is appreciably higher in BWR.
5. The pressure inside the pressure vessel is not high so a thicker vessel is not required.

Disadvantages :

1. Possibility of radioactive contamination in the turbine mechanism, should there be any failure of fuel elements.
2. More elaborate safety precautions needed which are costly.
3. Wastage of steam resulting in lowering of thermal efficiency on part load operation.
4. Boiling limits power density ; only 3 to 5% by mass can be converted to steam per pass through the boiler.
5. The possibility of "burn out" of fuel is more in this reactor than PWR as boiling of water on the surface of the fuel is allowed.

6.5.3. CANDU (Canadian-Deuterium-Uranium) Reactor

CANDU is a thermal nuclear power reactor in which *heavy water* (99.8% deuterium oxide D_2O) *is the moderator and coolant, as well as the neutron reflector.* This reactor was developed in Canada and is being extensively used in this company. A few CANDU reactors are operating or under construction in some other countries as well.

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In this type of reactor the *natural uranium* (0.7% U^{235}) *is used as fuel and heavy water as moderator.* These reactors are more economical to those countries which do not produce enriched uranium, as the *enrichment of uranium is very costly.*

CANDU (heavy water) reactor, differs basically from light-water reactors (LWRS) in that in the latter the *same water serves as both moderator and coolant*, whereas in the *CANDU reactor the moderator and coolant are kept separate.* Consequently unlike the pressure vessel of a LWR, the CANDU reactor vessel, which contains the relatively cool heavy water moderator, *does not have to withstand a high pressure. Only the heavy water coolant circuit has to be pressurised to inhibit boiling in the reactor core.*

Description of CANDU reactor

Fig. 6.14 shows the schematic arrangement of a CANDU reactor.

Reactor vessel and core. The reactor vessel is a steel cylinder with a horizontal axis ; the length and diameter of a typical cylinder being 6 m and 8 m respectively. The vessel is penetrated by some 380 horizontal channels called *pressure tubes* because they are designed to withstand a high internal pressure. The channels contain the fuel elements and the pressurised coolant flows along the channels and around the fuel elements to remove the heat generated by fission. Coolant flows in the opposite directions in adjacent channels.

The high pressure (10 MPa) and high temperature (370°C) coolant leaving the reactor core enters the steam generator. About 5% of fission heat is generated by fast neutrons escaping into the moderator, and this is removed by circulation through a separate heat exchanger.

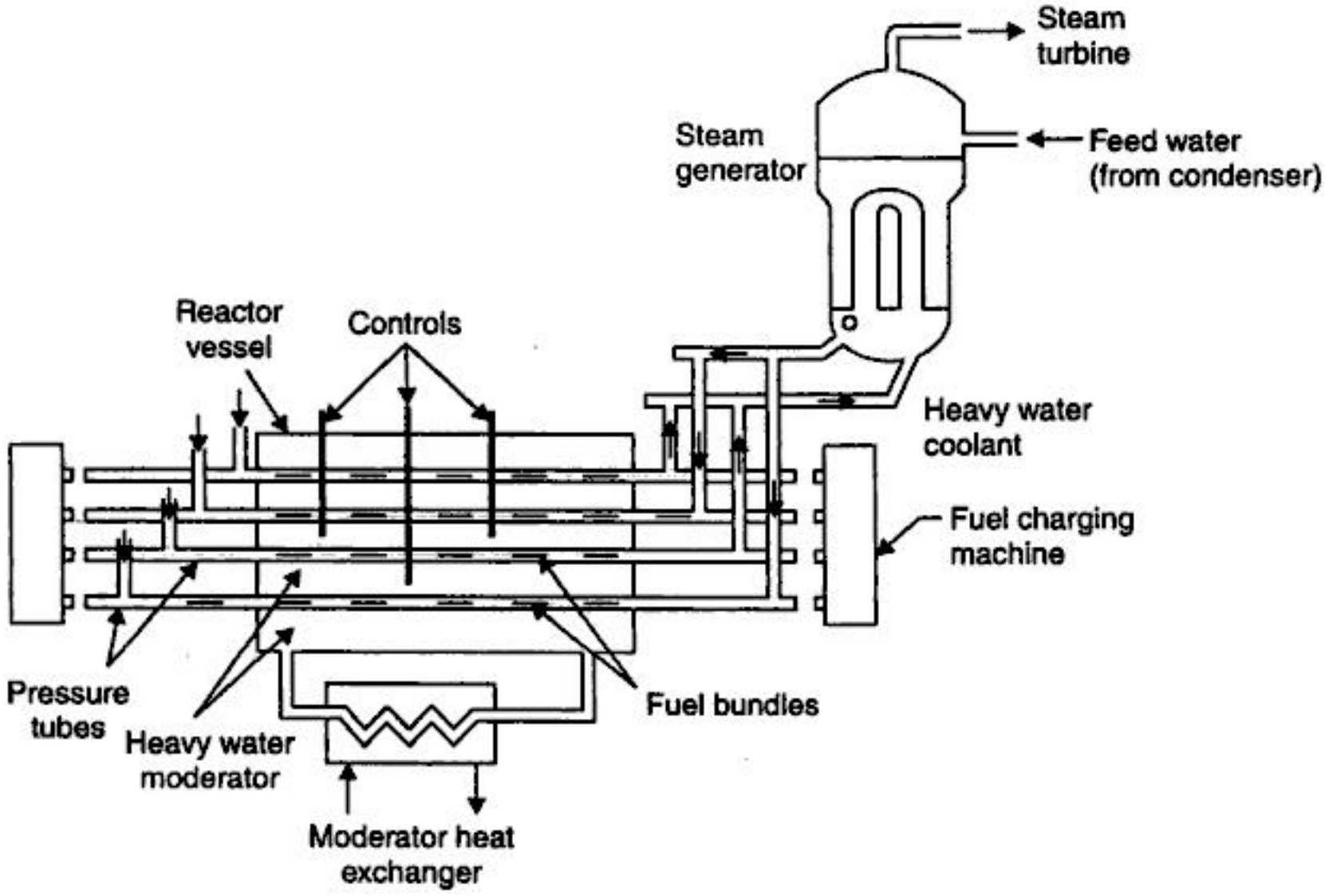

Fig. 6.14. CANDU reactor.

Fuel. In a CANDU reactor the fuel is *normal* (*i.e.*, unenriched) *uranium oxide* as small cylinder pellets. The pellets are packed in a corrosion resistance zirconium alloy tube, nearly 0.5 long and 1.3 cm diameter, to form a fuel rod. The relatively short rods are combined in bundles of 37 rods, and

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12 bundles are placed end to end in each pressure tube. The total mass of fuel in the core is about 97,000 kg. The CANDU reactor is *unusual in that refueling is conducted while the reactor is operating.*

Control and protection system :

There are the various types of vertical control system incorporated in the CANDU reactor :

— A number of strong neutron absorber *rods of cadmium* which are used mainly for *reactor shut-down* and *start-up.*

— In addition to above there are other *less strongly*, absorbing rods to *control power variations* during reactor operation and *to produce an approximately uniform heat* (power) distribution throughout the core.

In an emergency situation, the shut-down rods would immediately drop into the core, followed, if necessary by the injection of a gadolinium nitrate solution into the moderator.

Steam system. Steam system is discussed below :

— The respective ends of the pressure tubes are all connected into inlet and outlet headers.

— The high temperature coolant leaving the reactor passes out the outlet header to a steam generator of the conventional inverted U-tube and is then pumped back into the reactor by way of the inlet header.

— Steam is generated at a temperature of about 265°C.

There are two coolant outlet (and two inlet) headers, one at each end of the reactor vessel, corresponding to the opposite directions of coolant flow through the core. Each inlet (and outlet) header is connected to a separate steam generator and pump loop. A single pressurizer (of the type used in pressurised water reactors) maintains an essentially constant coolant system pressure.

The reactor vessel and the steam generator system are enclosed by a *concrete containment structure.* A water spray in the containment would condense the steam and reduce the pressure that would result from a large break in the coolant circuit.

Advantages of CANDU reactor :

1. Heavy water is used as moderator, which has higher multiplication factor and low fuel consumption.
2. Enriched fuel is not required.
3. The cost of the vessel is less as it has not to withstand a high pressure.
4. Less time is needed (as compared to PWR and BWR) to construct the reactor.
5. The moderator can be kept at low temperature which increases its effectiveness in slowing down neutrons.

Disadvantages :

1. It requires a very high standard of design, manufacture and maintenance.
2. The cost of heavy water is very high.
3. There are leakage problems.
4. The size of the reactor is extremely large as power density is low as compared with PWR and BWR.

6.5.4. Gas-Cooled Reactor

In such a type of reactor, the coolant used can be air, hydrogen, helium or carbondioxide. Generally inert gases are used such as helium and carbondioxide. The moderator used is *graphite.* The problem of corrosion is reduced much in such reactors. This type of reactor is more safe specially in case of accidents and the failure of circulating pumps. The thickness of gas cooled reactor shield is much reduced as compared to the other types of reactors.

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25. What is a 'Liquid metal-cooled reactor' ? Explain briefly a typical liquid metal reactor.
26. Describe a breeder reactor. What are its advantages and disadvantages ?
27. What factors must be considered while selecting materials for the various reactor components ?
28. List the advantages and disadvantages/limitations of nuclear power plants
29. Discuss the various factors which must be considered while selecting a site for a nuclear power plant.
30. Give the application of nuclear power plants.
31. What do you mean by 'Economics of nuclear power plants' ?
32. List down some safety measures for nuclear power plants.
33. What is the future of nuclear power ?

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7

Non-Conventional Power Generation and Direct Energy Conversion

7.1. Introduction. 7.2. Wind power plants—Introduction—Wind availability and measurement—Types of wind mills—Wind-electric generating power plant—Types of wind machines—Wind-powered battery chargers—Wind electricity in small independent grids—Wind electricity economics—Problems in operating large wind power generators. 7.3. Tidal power plants—Introduction—Components of tidal power plants—Classification and operation of tidal power plants—Advantages and limitations of tidal power generation. 7.4. Solar power plants—Solar energy—General terms and introduction—Collectors in various ranges and applications—Flat plate collectors—Focusing (or concentrating) collectors—Solar pond technology—Low temperature thermal power generation—Medium temperature systems using focusing collectors—High temperature systems—solar farm and solar tower plant. 7.5. Geothermal power plants—Geothermal energy—Geothermal sources—Geothermal power estimate—Environmental problems—Applications of geothermal energy—Advantages and disadvantages of geothermal energy over other energy forms. 7.6. Direct energy conversion systems—Thermoelectric conversion system—Thermionic conversion system—Photovoltaic power system—Magneto-hydrodynamics (MHD) system—Electrostatic mechanical generators—Electro gas-dynamic generators (EGD)—Fuel cells—Nuclear Batteries. Highlights—Theoretical Questions.

7.1. INTRODUCTION

A plenty of energy is needed to sustain industrial growth and agricultural production. The existing sources of energy such as coal, oil, uranium etc. may not be adequate to meet the ever increasing energy demands. These conventional sources of energy are also depleting and may be exhausted at the end of the century or beginning of the next century. Consequently sincere and untiring efforts shall have to be made by the scientists and engineers in exploring the possibilities of harnessing energy from several non-conventional energy sources. The various non-conventional energy sources are as follows :

(*i*) Solar energy
(*ii*) Wind energy
(*iii*) Energy from biomass and biogas
(*iv*) Ocean thermal energy conversion
(*v*) Tidal energy
(*vi*) Geothermal energy
(*vii*) Hydrogen energy
(*viii*) Fuel cells
(*ix*) Magneto-hydrodynamics generator
(*x*) Thermionic converter
(*xi*) Thermo-electric power.

Advantages of non-conventional energy sources :

The *leading advantages* of non-conventional energy sources are :

1. They do not pollute the atmosphere.
2. They are available in large quantities.
3. They are well suited for decentralised use.

According to energy experts the non-conventional energy sources can be used with advantage for *power generation* as well as other applications in a large number of locations and situations in our country.

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7.2. WIND POWER PLANTS

7.2.1. Introduction

The electrical energy can be generated by wind energy. The wind energy, which is an indirect source of energy, can be used to run a wind will which in turn drives a generator to produce electricity. Although wind mills have been used for more than a dozen centuries for grinding grain and pumping water, interest in large scale power generation has developed over the past 50 years. A largest wind generator built in the past was 800 kW unit operated in France from 1958-60. The flexible 3 blades propeller was about 35 m in diameter and produced the rated power in a 60 km/hour wind with a rotation speed of 47 r.p.m. The maximum power developed was 12 MW. In India the interest in the wind mills was shown in the last fifties and early sixties. Apart from importing a few from outside, new designs were also developed, but they did not sustain. It is only in last 10—15 years that development work is going on in many institutions. An important reason for this lack of interest in wind energy must be that wind, in India is relatively low and vary appreciable with seasons. These low and seasonal winds imply a high cost of exploitation of wind energy. In our country high wind speeds are however available in coastal areas of Sourashtra, Western Rajsthan and some parts of central India. In these areas there could be a possibility of using medium and large sized wind mills for generation of electricity.

Characteristics of wind energy :

1. Wind-power systems do not pollute the atmosphere.
2. Fuel provision and transport are not required in wind-power systems.
3. Wind energy is a renewable source of energy.
4. Wind energy when produced on small scale is cheaper, but competitive with conventional power generating systems when produced on a large scale.

Wind energy entails following *shortcomings/problems* :

1. It is fluctuating in nature.
2. Due to its irregularity it needs storage devices.
3. Wind power generating systems produce ample *noise*.

7.2.2. Wind Availability and Measurement

Wind energy can only be economical in areas of good wind availability. Wind energy differs with region and season and also, possibly to an even greater degree with local terrain and vegetation. Although wind speeds generally increase with height, varying speeds are found over different kinds of terrain. Observations of wind speed are carried out at meteorological stations, airports and lighthouses and are recorded regularly with ten minute mean values being taken every three hours at a height of 10 m. But airports, sometimes are in valleys and many wind speed meters are situated low and combinations of various, other factors mean that reading can be misleading. It is difficult, therefore, to determine the real wind speed of a certain place without actual in-situ measurements.

The World Meteorological Organization (WMO) has accepted four methods of wind recording :

(*i*) Human observation and log book.

(*ii*) Mechanical cup-counter anemometers.

(*iii*) Data logger.

(*iv*) Continuous record of velocity and direction.

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1. **Human observation and log book.** This involves using the Beaufort Scale of wind strengths which defines visible "symptoms" attributable to different wind speeds. The method is *cheap* and *easily implemented* but is *often unreliable*. The best that can be said of such records is that they are better than nothing.

2. **Mechanical cup-counter anemometers.** The majority of meteorological stations use mechanical cup-counter anemometers. By taking the readings twice or three times a day, it is possible to estimate the mean wind speed. This is a *low cost method*, but is *only relatively reliable*. The instrument has to be in good working order, it has to be correctly sited and should be reliably read at least daily.

3. **Data logger.** The equipment summarizes velocity frequency and direction. It is *more expensive and prone to technical failures but gives accurate data*. The method is tailored to the production of readily interpretable data of relevance to wind energy assessment. It does not keep a time series record but *presents the data in processed form*.

4. **Continuous record of velocity and direction.** This is how data is recorded at major airports of permanently manned meteorological stations. The *equipment is expensive and technically complex*, but it retains a detailed times-series record (second-by-second) of wind direction and wind speed. Results are given in copious quantities of data which require lengthy and expensive analysis.

7.2.3. Types of Wind Mills

The various types of wind mills which are practically useful are shown in Fig. 7.1.

1. **Multiple blade type.** It is the most widely used wind mill. It has 15 to 20 blades made from metal sheets. The *sail type* has three blades made by stitching out triangular pieces of convass cloth. Both these types run at low speeds of 60 to 80 r.p.m.

2. **Savonius type.** This type of windmill has hollow circular cylinder sliced in half and the halves are mounted on vertical shaft with a gap in between. Torque is produced by the pressure difference between the two sides of the half facing the wind. This is quite efficient but needs a large surface area.

3. **Darrieus type.** This wind mill needs much less surface area. It is shaped like an egg beater and has two or three blades shaped like aerofoils.

It may be noted that :

— Both the Savonius and Darrieus types are mounted on a *vertical axis* and hence they *can run independently of the direction of wind.*

— The horizontal axis mills *have to face the direction of the wind* in order to generate power.

Performance of wind mills :

The performance of a wind mill is defined as *'Co-efficient of performance'* (K_p).

$$K_p = \frac{\text{Power delivered by the rotor}}{\text{Maximum power available in the wind}}$$

or,
$$K_p = \frac{P}{P_{max}} = \frac{P}{\frac{1}{2}\rho A U_w^{\,3}}$$

where, ρ = Density of air,

A = Swept area, and

U_w = Velocity of wind.

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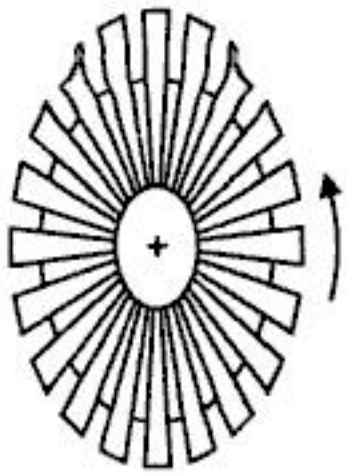
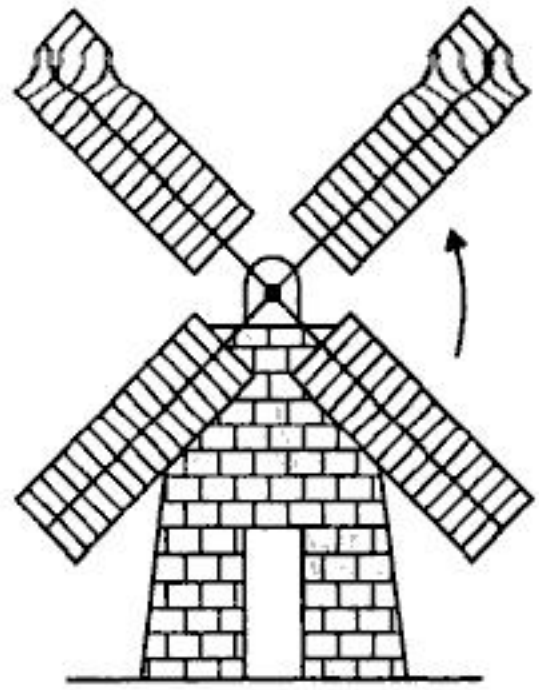
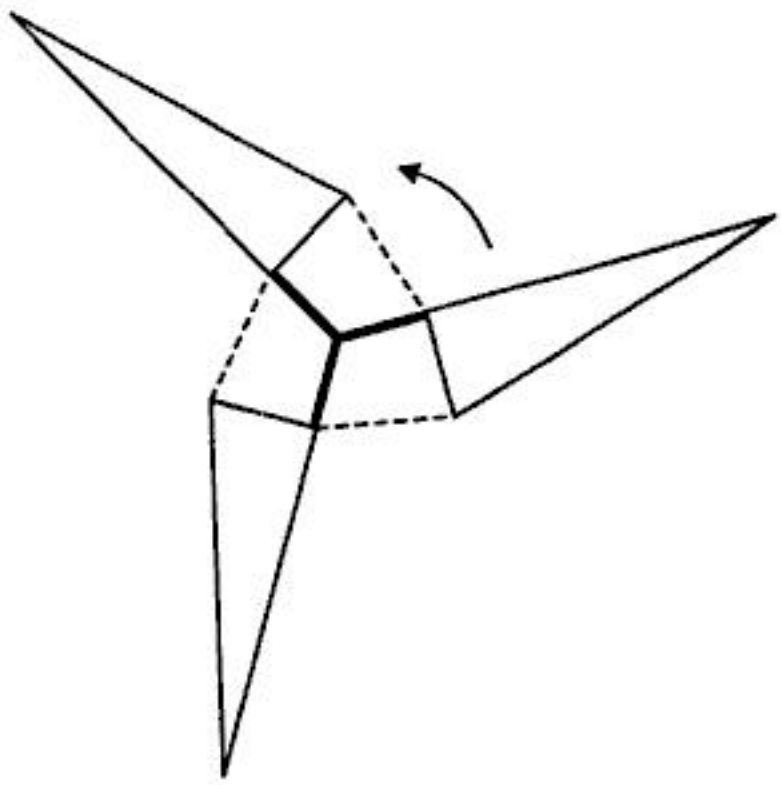


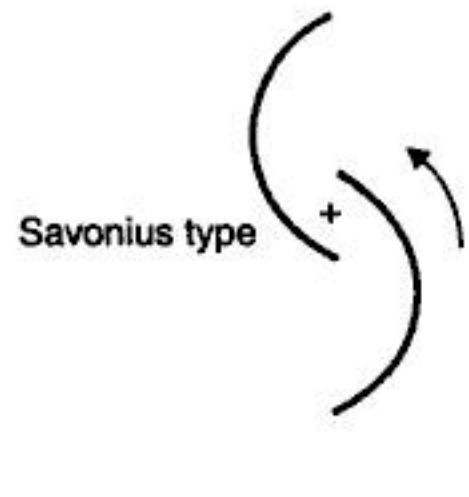
Multiblade type



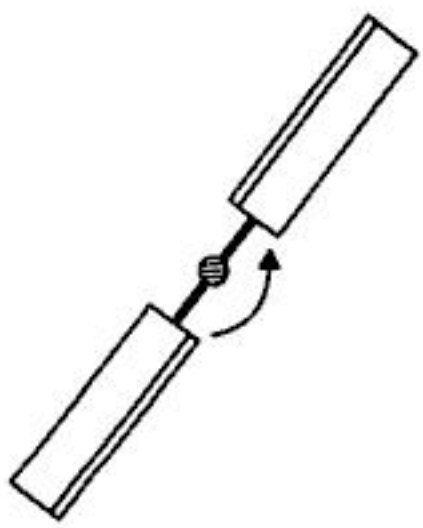
Four-blade Dutch wind mill



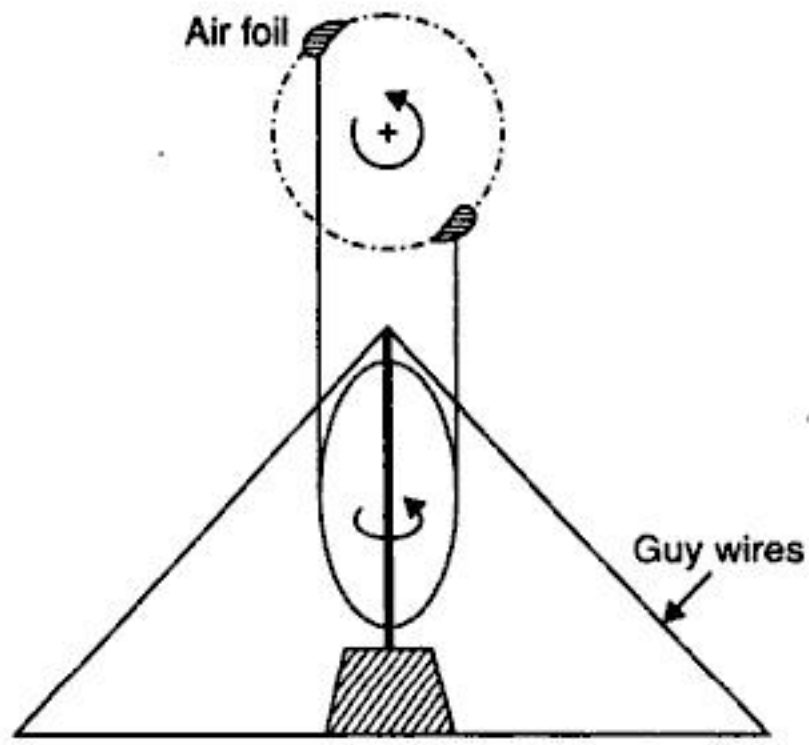
Sail type



Savonius type



Propeller type



Darrieus type

Fig. 7.1. Types of wind mills.

Fig. 7.2 shows a plot between K_p and tip speed ratio U_{bt}/U_w

where U_{bt} = Speed of blade tip.

It can be seen that K_p is the *lowest of Savonius* and *Dutch types* whereas the *propeller types have the highest value*.

In the designing of wind mills, it is upper most to keep the power to weight ratio at the lowest possible level.

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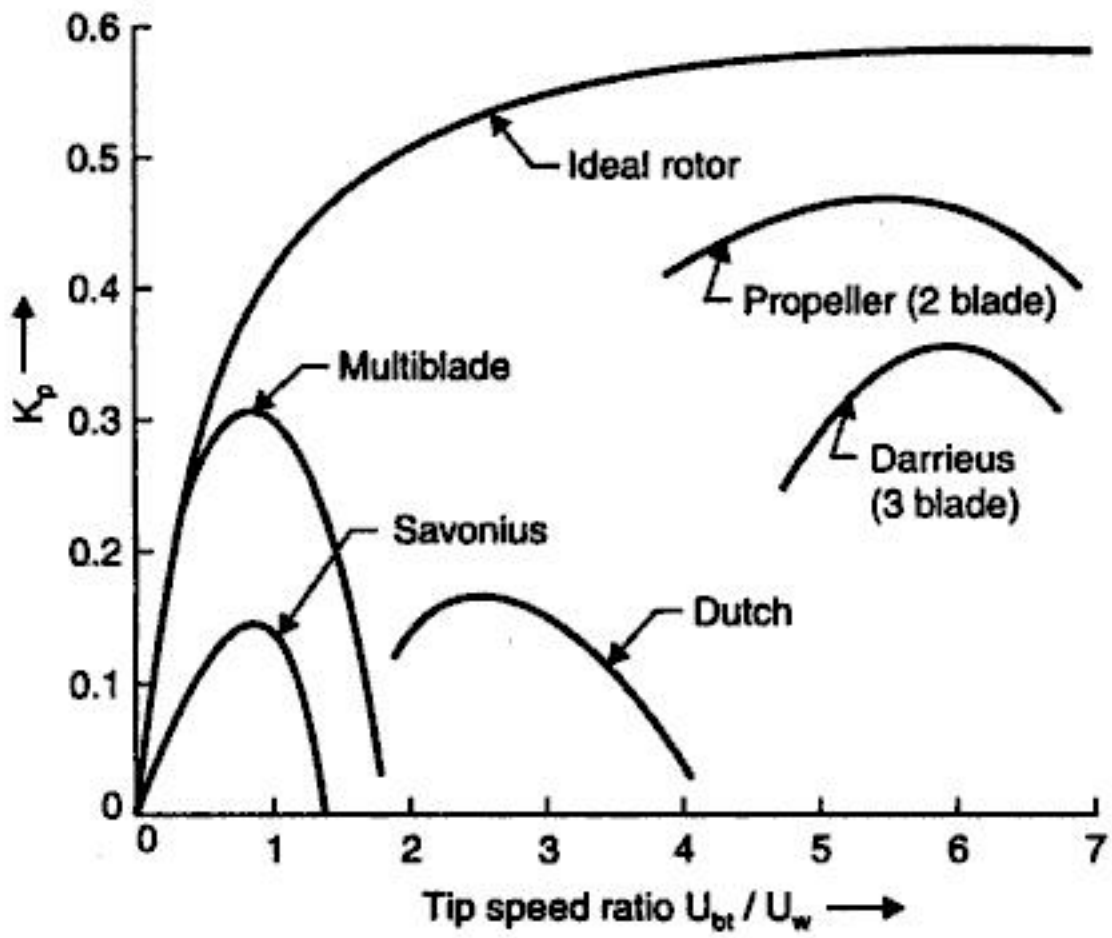

Fig. 7.2. K_p of wind mills.

7.2.4. Wind-Electric Generating Power Plant

Fig. 7.3 shows the various parts of a wind-electric generating power plant. These are :

1. Wind turbine or rotor.
2. Wind mill head—it houses speed increaser, drive shaft, clutch, coupling etc.

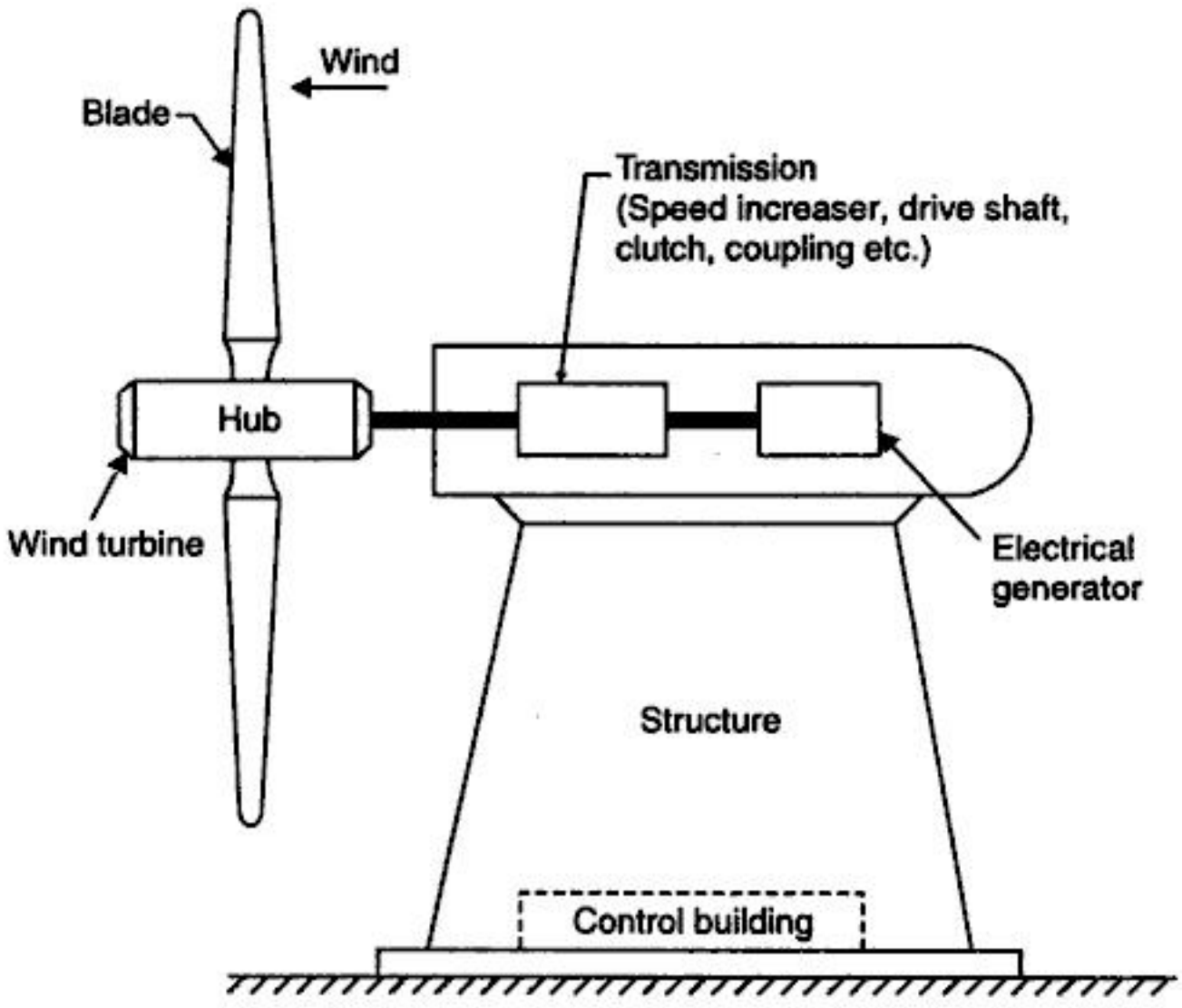

Fig. 7.3. Wind-electric generating power plant.

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3. Electrical generator.

4. Supporting structure.

— The most important component is the **rotor.** For an effective utilisation, all components should be properly designed and matched with the rest of the components.

— The wind mill head performs the following *functions* :

(*i*) It supports the rotor housing and the rotor bearings.

(*ii*) It also houses any control mechanism incorporated like changing the pitch of the blades for safety devices and tail vane to orient the rotor to face the wind, the latter is facilitated by mounting it on the top of the supporting structure on suitable bearings.

— The wind turbine may be located either *unwind* or *downwind* of the power. In the unwind location the wind encounters the turbine before reaching the tower. *Downwind rotors are generally preferred especially for the large aerogenerators.*

— The **supporting structure** is designed to withstand the wind load during gusts. Its type and height is related to cost and transmission system incorporated. Horizontal axis wind turbines are mounted on towers so as to be above the level of turbulence and other ground related effects.

7.2.5. Types of Wind Machines

Wind machines (aerogenerators) are generally *classified* as follows :

1. Horizontal axis wind machines.

2. Vertical axis wind machines.

Horizontal axis wind machines. Fig 7.4 shows a schematic arrangement of a horizontal axis machine. Although the common wind turbine with a horizontal axis is simple in principle,

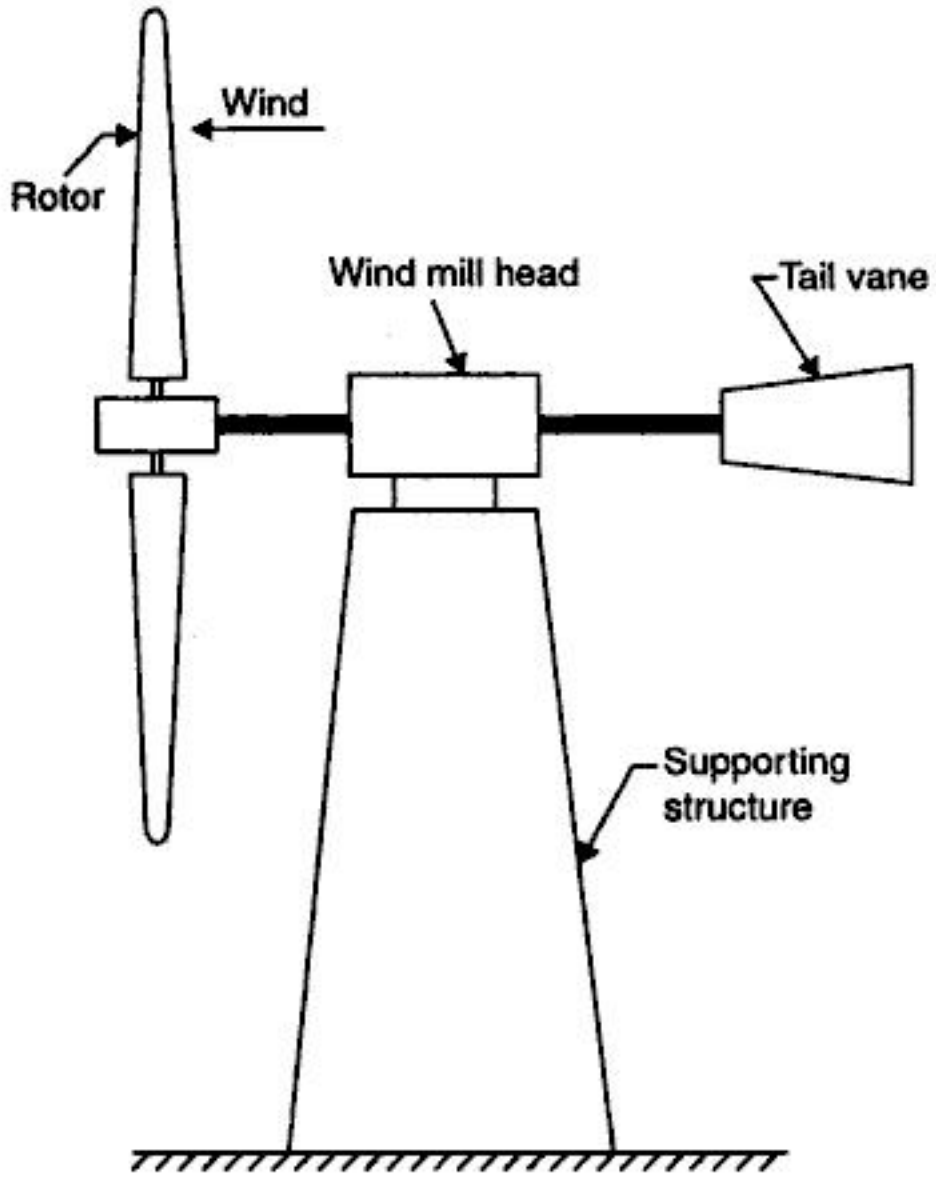

Fig. 7.4. Horizontal axis wind machine.

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yet the design of a complete system, especially a large one that would produce electric power economically, is complex. It is of paramount importance that the components like rotor, transmission, generator and tower should not only be as efficient as possible but they must also function effectively in combination.

Vertical axis wind machines. Fig. 7.5 shows vertical axis type wind machine. One of the main advantages of vertical axis rotors is that they do not have to be turned into the windstream as the wind direction changes. Because their operation is independent of wind direction, vertical axis machines are called *panemones*.

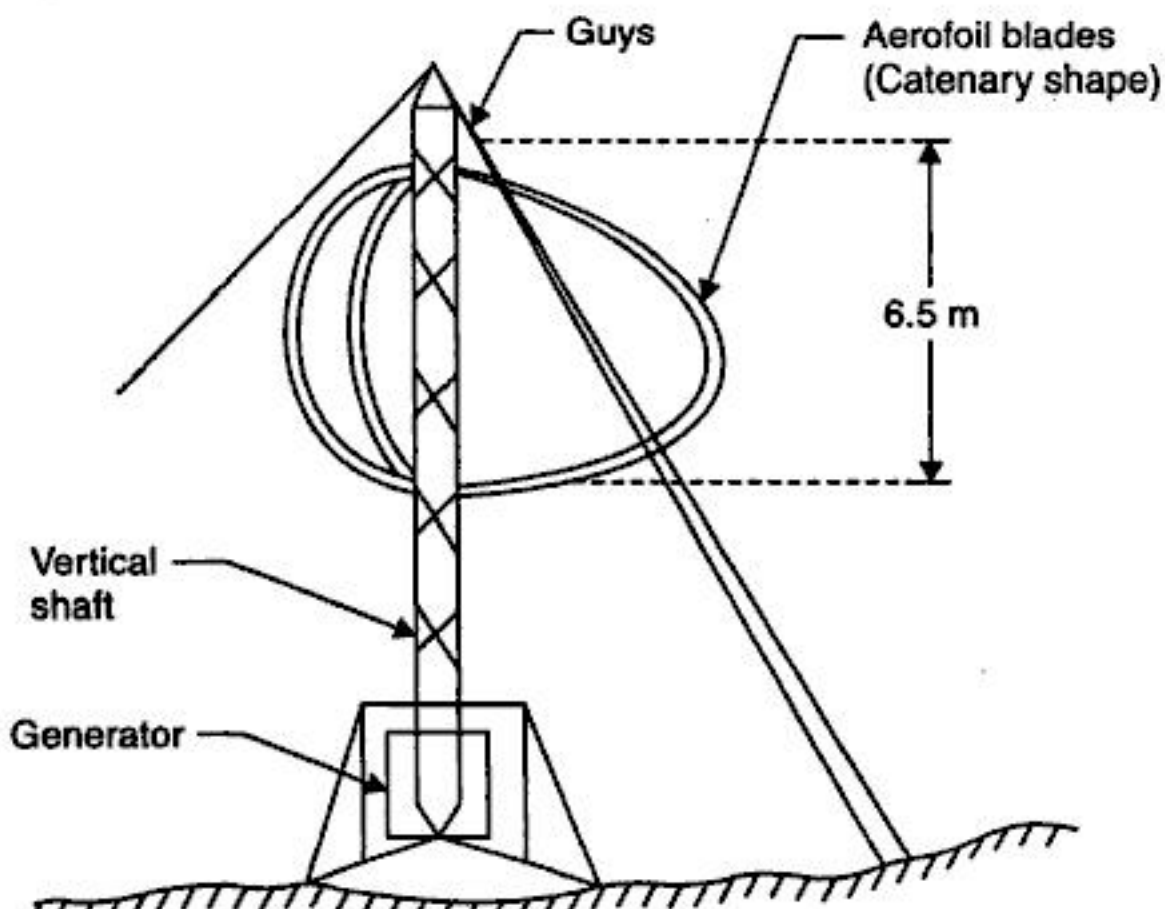

Fig. 7.5. Vertical axis wind machine.

7.2.6. Wind-Powered Battery Chargers

One application of wind energy systems which is of considerable potential importance (to developing countries) is the use of small wind generators to charge batteries for powering lighting, radio communication and hospital equipment. Wind generators have been in use in Europe and North America since the 1920s, although their use declined considerably.

A battery charging system has to include the following :

(*i*) A wind powered generator.

(*ii*) A converter.

(*iii*) A container for the batteries.

Fig. 7.6 shows a set-up of wind powered battery charging system. It is worthnoting that 12 volt batteries, which are rechargeable using wind generators, can be used to power fluorescent tube lighting which is six times more efficient than tungsten filament lamps. Such lighting opens up a number of important development opportunities in areas which normally have no lighting.

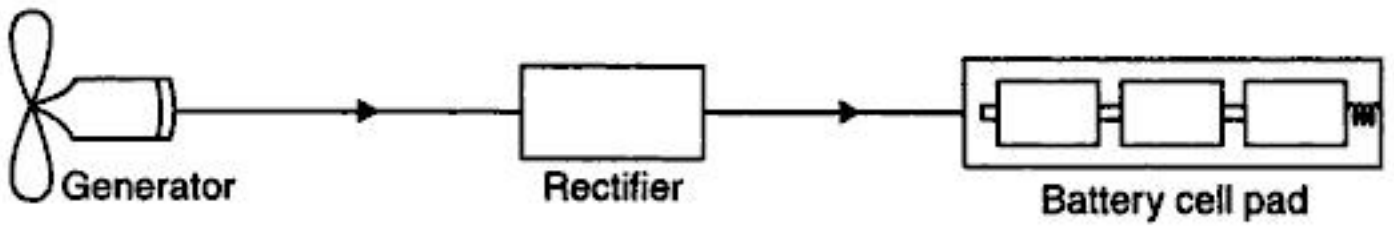

Fig. 7.6

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For small wind generators the total system efficiency is made up as follows :

Wind regime matching efficiency	60% (approx.)
Rotor efficiency	35% (approx.)
Generator and wiring efficiency	70% (approx.)
Battery charge/discharge efficiency	70% (approx.)

Cumulatively, a total energy capture efficiency of about 10% is generally obtained from small wind generators utilized for battery charging.

Battery charging wind generators are produced in several countries, notably Australia, France, Sweden, Switzerland, the U.K., the U.S.A. and West Germany. In developing countries production is underway in China and has started in India.

7.2.7. Wind Electricity in Small Independent Grids

Refer to Fig. 7.7. In such systems electricity consumption fluctuates constantly as does the availability of wind energy. The degree of coincidence of supply and demand can be calculated by statistical means and it has been found that electricity supply with an acceptable degrees of reliability cannot be based solely on wind energy. If an extensive grid does not exist, electricity storage (batteries) or a back-up system (diesel) is required. Loads for remote systems of upto 6 kWh/day equivalent to an average power consumption of 250 W with a duty cycle of 24 hours, can be provided with battery storage.

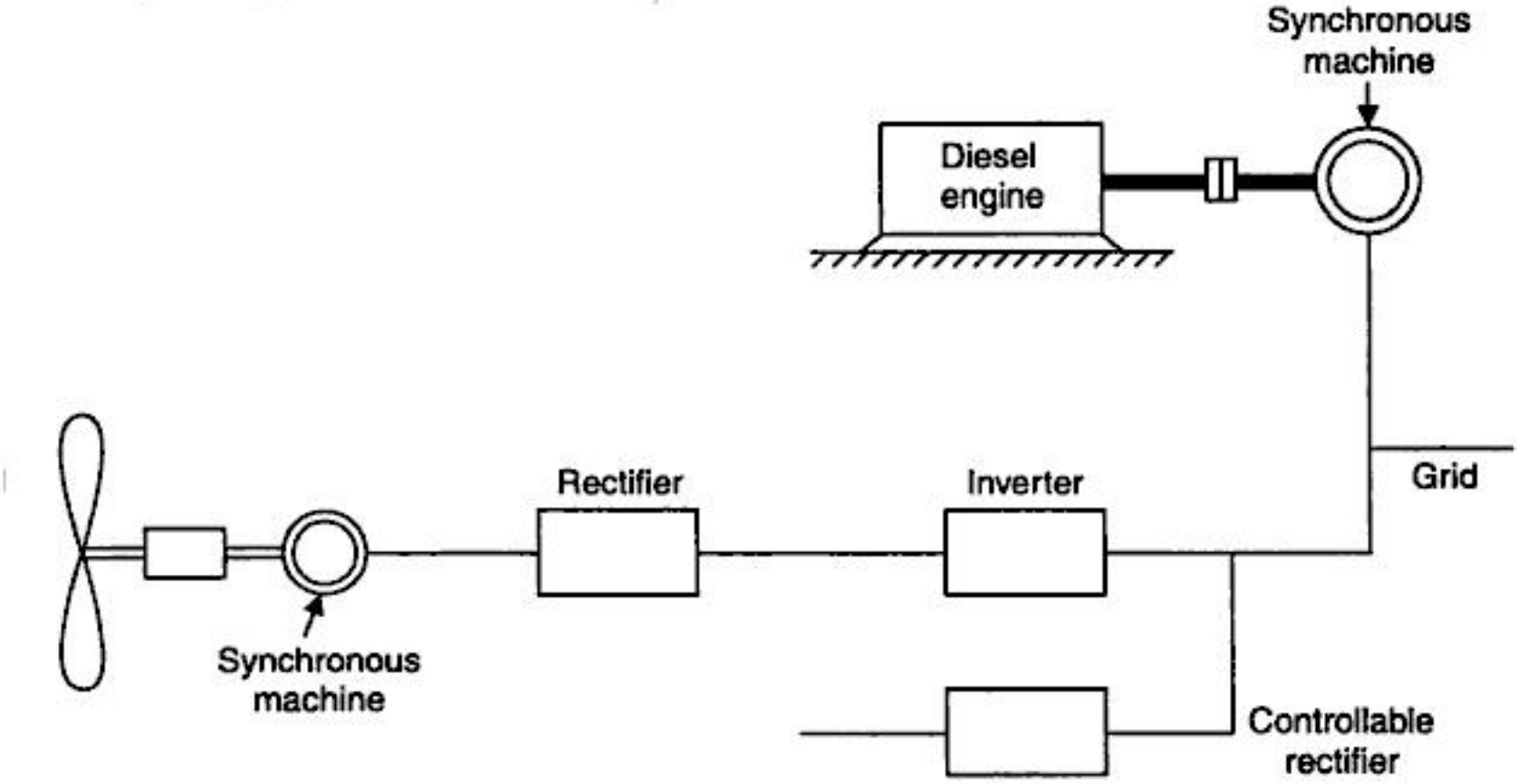

Fig. 7.7. Principle of combined wind/diesel power generation.

If a diesel and wind generator are used in conjunction with a grid, the *diesel generator should only be used when wind energy is absent*. Problems can occur, however, when the diesel generator is called on to change its output frequently as wind energy availability fluctuates. Besides decreasing the oil saving, diesel generation on this basis leads to more frequent overhauls of the generator. Both factors will increase costs. Several methods of overcoming these problems have been tried but there is not yet an established solution. Some development work has still to be done before wind generators can be run in parallel with diesel on a routine basis.

7.2.8. Wind Electricity Economics

Wind generator power costs are heavily linked to the characteristics of a wind resource in a specific location. The cost of supplied power declines as wind speeds increase, and the power supplied increases in proportion to the *cube of the wind speed.*

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Matching available energy and load requirements is also important in wind energy economics. The correct size of wind generator must be chosen together with some kind of storage or cogeneration with an engine or a grid to obtain the best economy. The ideal application is a task that can utilize a variable power supply, *e.g.*, ice making or water purification.

Regarding the *economics*, the choice of interest rate obviously has a major effect on the overall energy cost. With low interest rates, capital intensive power sources such as solar and wind are favoured. Other factors bearing a strong influence on the economics of wind electricity are the standard of maintenance and service facilities and the cost of alternative energy supplies in the particular area.

7.2.9. Problems in Operating Large Wind Power Generators

The operation of large wind power generators entails the following *problems* :

1. **Location of site.** The most important factor is locating a site big enough which has a reasonable average high wind velocity.

Sourastra and Coastal Regions in India are promising areas.

2. **Constant angular velocity.** A constant angular velocity is a must for generating A.C. (alternating current) power and this means very sensitive governing.

3. **Variation in wind velocity.** The wind velocity varies with time and varies in direction and also varies from the bottom to top of a large rotor (some rotors are as long as 50 meters). This causes fatigue in blades.

4. **Need of a storage system.** At zero velocity conditions, the power generated will be zero and this means some storage system will have to be incorporated along with the wind mill.

5. **Strong supporting structure.** Since the wind mill generator will have to be located at a height, the supporting structure will have to be designed to withstand high wind velocity and impacts. This will add to the initial costs of the wind mill.

6. **Occupation of large areas of land.** Large areas of land will become unavailable due to wind mill gardens (places where many wind mills are located). The whole area will have to be protected to avoid accidents.

Inspite of all these difficulties, interest to develop wind mills is there since this is a clean source of energy.

7.3. TIDAL POWER PLANTS

7.3.1. Introduction

The periodic rise and fall of the water level of sea which are carried by the action of the sun and moon on water of the earth is called the **'tide'**. Tidal energy can furnish a significant portion of all such energies which are renewable in nature. The large scale up and down movement of sea water represents an unlimited source of energy. If some part of this vast energy can be converted into electrical energy, it would be an important source of hydropower.

The *main feature of the tidal cycle is the difference in water surface elevations at the high tide and at the low tide.* If this differential head could be utilized in operating a hydraulic turbine, the tidal energy could be converted into electrical energy by means of an attached generator.

7.3.2. Components of Tidal Power Plants

The following are the *components* of a tidal power plant :

1. The dam or dyke (low wall) to form the pool or basin.
2. Sluice ways from the basins to the sea and *vice versa*.
3. The power house.

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Dam or dyke. The function of dam or dyke is to form a barrier between the sea and the basin or between one basin and the other in case of multiple basins.

Sluice ways. These are used to fill the basin during the high tide or empty the basin during the low tide, as per operational requirement. These devices are controlled through gates.

Power house. A power house houses turbines, electric generators and other auxiliary equipment. As far as possible the power house and sluice ways should be in *alignment* with the dam or dyke.

7.3.3. Classification and Operation of Tidal Power Plants

Tidal power plants are *classified* as follows :

1. Single basin arrangement

(*i*) Single ebb-cycle system (*ii*) Single tide-cycle system

(*iii*) Double cycle system.

2. Double basin arrangement

In a *single basin arrangement* power can be generated only *intermittently*. In this arrangement only one basin interacts with the sea. The two are separated by a dam or dyke and the flow between them is through sluice ways located conveniently along the dam. The rise and fall of tidal water levels provide the potential head.

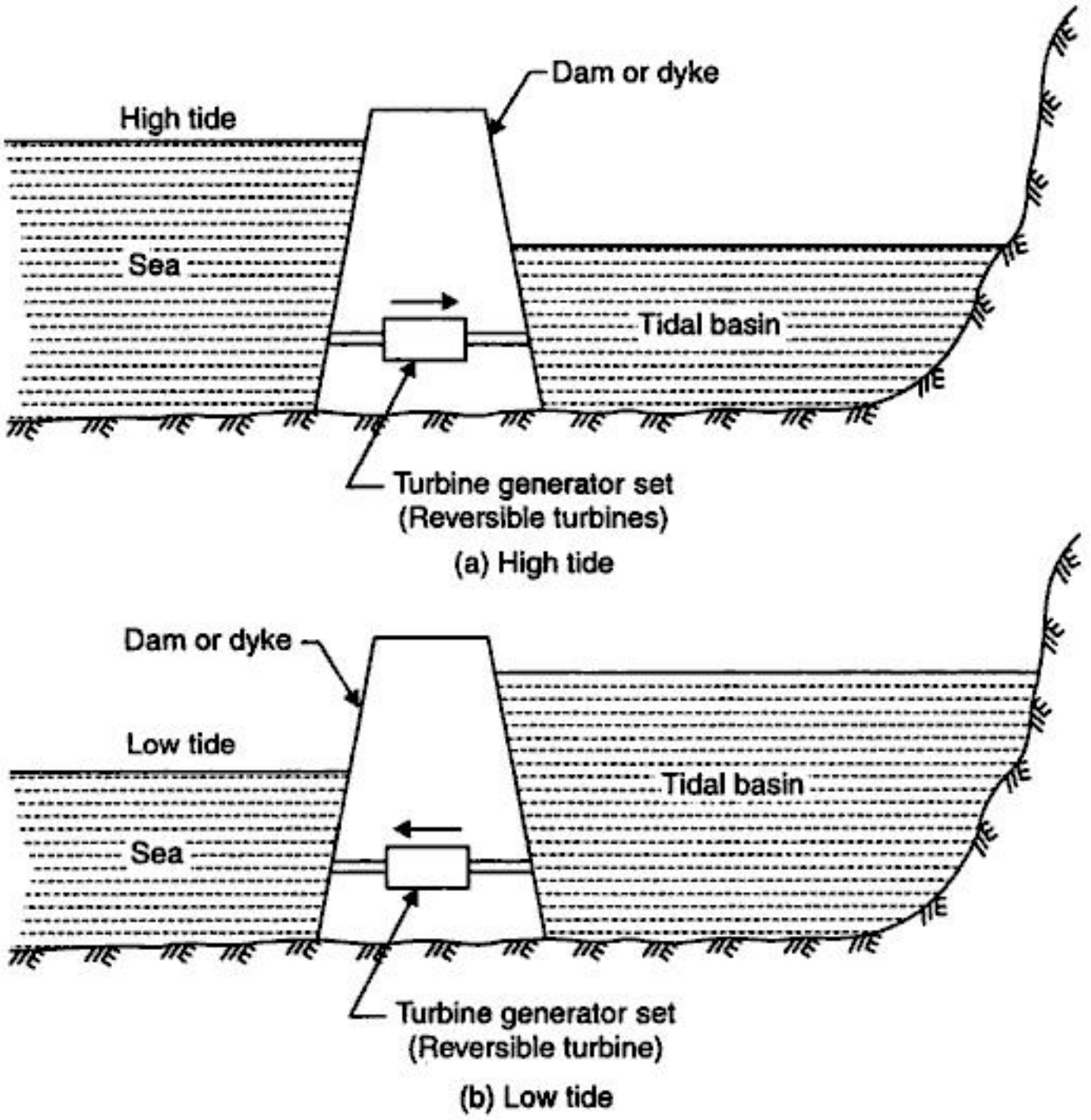

Fig. 7.8. General arrangement of tidal power plant.

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(*ii*) have *low emissivity*, to reduce heat transfer by radiation from the emitter.

(*iii*) be such that in the event some of it vaporizes and subsequently condenses on the collector it will not poison the collector (that is, change the collector properties, thereby making it less effective).

The relative importance of these properties is dependent upon the type of converter being designed. It should be noted that efficiency is a much slower rising function of electron emission capability if space charge is present than if there is no space charge.

The work function may be reduced considerably by an absorbed single layer of foreign atoms. This comes about by the establishment of a dipole layer at the surface. The layer can be formed by atoms or molecules. This is essentially what happens in a cesium converter, which is designed so that cesium condenses on the emitter or collector.

Collector. The *main criteria for choosing a collector material is that it should have as low a work function as possible*. Because the collector temperature is held below any temperature that will cause significant electron emission, its actual emission characteristics are of no consequence. The lower the collector work function (ϕ_c), however the less energy the electron will have to give up as it enters the collector surface. In practice the lowest value of ϕ_c that can be maintained stably is about 1.5 eV. For applications in which it is desirable to maintain the collector at elevated temperatures (greater than 900°K) such as space applications, an optimum value of ϕ_c may be determined. Molybdenum has been widely used as a collector ; it is frequently assumed to have a work function of 1.7 eV.

7.6.3. Photovoltaic Power System

Photovoltaic generators—Historical background. Edmond Becquerel in 1839 noted that a voltage was developed when light was directed onto one of the electrodes in an electrolytic solution. The effect was first observed in a solid in 1877 by W.G. Adams and R.E. Day, who conducted experiments with selenium. Other early workers with solids included Schottky, Lange and Grandahl, who did pioneering work in producing photovoltaic cells with selenium and cuprous oxide. This work led to the development of photoelectric exposure meters. 1954 researchers turned to the problem of utilizing the photovoltaic effect as a source of power. In that year several groups including the workers at Bell Telephone Laboratories achieved conversion efficiencies of about 6 per cent by means of junctions of *P*-type and *N*-type semiconductors. These early junctions, commonly called *P-N* junctions, were made of cadmium sulphide and silicon. Later workers in the area have achieved efficiencies more than 20 per cent by using improved silicon *P-N* junctions.

Photovoltaic cell. Solar energy can be directly converted to electrical energy by means of *photovoltaic effect* which is defined as the *generation of an electromotive force as a result of the absorption of ionizing radiation*. Energy conversion devices which are employed to convert sunlight into electricity by the use of the photovoltaic effect are called *solar cells*. A single converter cell is called a solar cell or a *photovoltaic cell*. To increase the electrical power output a number of such cells are combined and the combination is called a *solar array* (or solar module).

In a photovoltaic cell sensitive element is a *semiconductor* (not metal) which generates voltage in proportion to the light or any radiant energy incident on it. The most commonly used photovoltaic cells are barrier layer type like iron-selenium cells or Cu—CuO_2 cells.

Fig. 10.26 shows a typical widely used photo-voltaic cell—"*Selenium cell*". It consists of a metal electrode on which a layer of selenium is deposited ; on the top of this a barrier layer is formed which is coated with a very thin layer of gold. The latter serves as a translucent electrode through which light can impinge on the layer below. Under the influence of this light, a negative charge will build up on the gold electrode and a positive charge on the bottom electrode.

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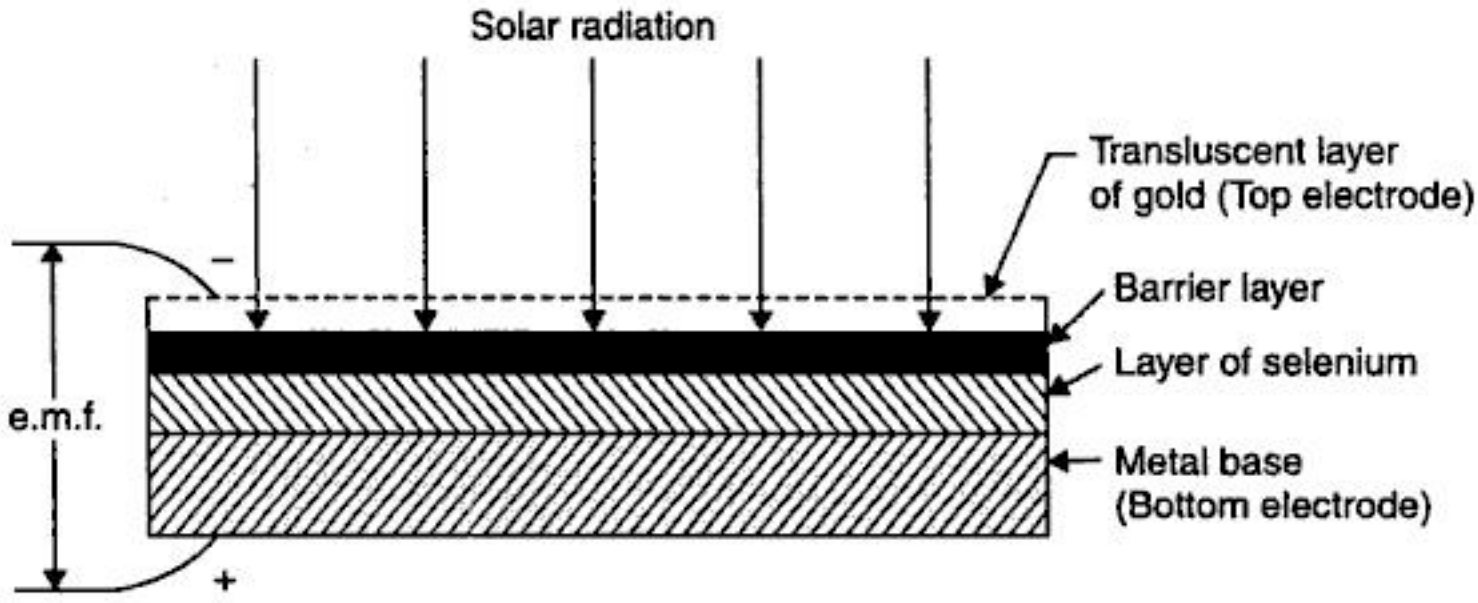

Fig. 7.26. Photovoltaic cell.

Photovoltaic cells are widely used in the following fields :

(*i*) Automatic control systems.

(*ii*) Television circuits.

(*iii*) Sound motion picture and reproducing equipment.

Basic photovoltaic system for power generation :

Fig 7.27 shows a basic photovoltaic system integrated with the utility grid. With the help of this system the generated electrical power can be delivered to the local load.

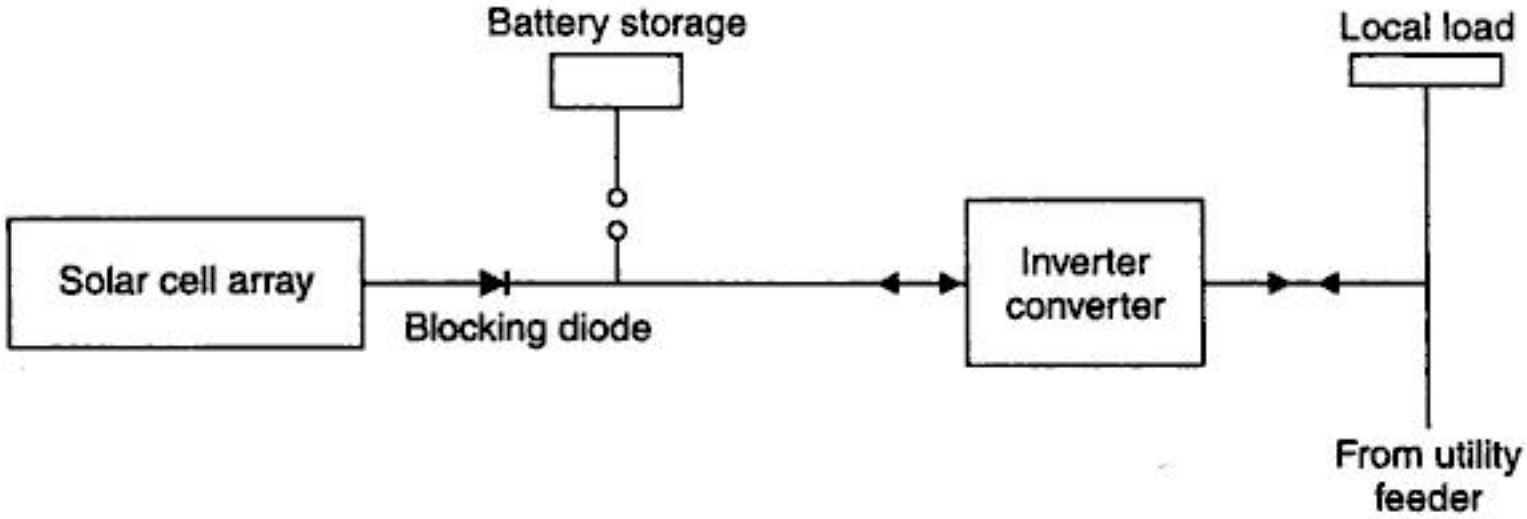

Fig. 7.27. Basic photovoltaic system integrated with power grid.

This system consists of the following :

1. Solar array
2. Blocking diode
3. Battery storage
4. Inverter converter
5. Switches and circuit breakers.

— The *solar array* (large or small) converts the insolation to useful D.C. electrical power.

— The *blocking diode* confines the electrical power generated by the solar array to flow towards the battery or grid only. In the absence of blocking diode the battery would discharge back (through the solar array) during the period when there is no insolation.

— *Battery storage* stores the electrical power generated through solar array.

— *Inverter/converter* (usually solid state) converts the battery bus voltage to A.C. of frequency and phase to match that needed to integrate with the utility grid. Thus it is typically a D.C., A.C. inverter.

— *Switches and circuit breakers* permit isolating parts of the system, as the battery.

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Limitations of photovoltaic energy converters

The major factors which prohibit real photovoltaic converters from achieving the higher efficiencies are :

1. Reflection losses on the surface.
2. Incomplete absorption.
3. Utilization of only part of the photon energy for creation of electron hole pairs.
4. Incomplete collection of electron-hole pairs.
5. A voltage factor.
6. A curve factor related to the operating unit at maximum power.
7. Additional delegation of the curve due to internal series resistance.

Fabrication of Cells :

A. Silicon cells :

Silicon cells are most widely used. Next to oxygen, silicon is the most abundant element on earth, the pure silicon used in cell manufacture is extracted from sand which is mostly silicon dioxide (SiO_2). The silicon required for solar cell use, because of its high purity, is expensive.

The fabrication of silicon cells include the following steps :

(*i*) The pure silicon is placed in an induction furnace where boron is added to melt. This turns the crystal resulting from the melt into *P*-type material.

(*ii*) A small seed of single crystal silicon is dipped into the melt and withdrawn at a rate slower than 10 cm per hour, the resulting inset looks like a medium sized carrot. The rate of growth and other conditions are adjusted so that the crystal that is pulled is a single crystal.

(*iii*) Wafers are then sliced from the grown crystal by the use of a diamond cutting wheel. The slices are then lapped, generally by hand, to remove the saw marks and strained regions.

(*iv*) After a fine lap the slabs are etched in hydrofluoric acid or nitric acid to complete the first phase of preparation of the cells. We now have thin slices of *P*-type silicon with a carefully finished surface.

(*v*) The wafers are then sealed in a quartz tube partly filled with phosphorous pentoxide and the arrangement is placed in a diffusion furnace where temperature is carefully controlled ; this process causes the phosphorous to diffuse into the *P*-type silicon to a depth of about 10^{-4} cm to 10^{-5} cm.

(*vi*) The cells are then etched in a concentrated acid to remove unwanted coatings that formed during manufacture. Wax or Teflon masking tape is used to protect the surfaces not to be etched.

B. Thin film solar cells :

These cells have the following *advantages :*

(*i*) The material cost is low.

(*ii*) The manufacturing cost is low (possibly avoiding the need for single crystal growth).

(*iii*) High power-to-weight ratios.

(*iv*) Low array costs, because the number of connections needed will be greatly reduced.

The example of this type of cell is cadmium sulphide (CdS) cells. CdS cells having areas of 50 cm^2 have been made by evaporating the semiconductor on to a flexible substrate such as kapton, a metallized plastic substrate. A barrier layer of copper sulphide is then deposited on top of the CdS.

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7. The interconnection of different power plants reduces the amount of generating capacity required to be installed as compared to that which would be required without interconnection.
8. In an interconnected system the spinning reserve required is reduced.

8.3. LOAD DIVISION BETWEEN POWER STATIONS

Under the situation when the load curve has a very high peak value, it is usually supplied for two or more power stations/services by interconnection. In that case, total load as shown on load duration curve may be divided into following two parts :

(*i*) The base load (*ii*) The peak load.

***Base load** is supplied by one power station and the other power station takes care of the **peak load**.* In such cases the *load is economically apportioned to various systems in order to achieve the overall economy.*

In such cases it is not very necessary to interconnect the two systems of the *same type*. For example, if the base load is supplied by the steam power station, then it is not very necessary that the peak load may also be supplied by the steam power station. A hydro-electric power station can very well be adopted for supplying the peak load. Similarly, a hydro-electric station can be used for supplying the base load and in that case the peak load can be supplied by steam power station or a diesel engine station or any other suitable unit. However the selection of the power stations for supplying the base load or peak load is made on the basis of the requirements and ability of the various power stations/services to meet those requirements.

Requirements of a plant supplying the *'Base load'* :

1. Minimum operation cost.
2. Continuous supply of the load.
3. Capital cost of the plant should be minimum.
4. Requirement of plant maintenance should be minimum.
5. Plant should be such that it can be easily located near the load centre.
6. The number of operators required should be minimum.
7. The spare parts etc. should be readily available.

Taking into view the above requirements, let us now consider various types of plants for their suitability to meet the base load.

Hydro-electric stations. (*i*) In these plants the *operating cost is minimum* as practically *no fuel* is required for the purpose of power generation, and as such there is no problem of procurement of the fuel.

(*ii*) *Maintenance cost is lower* than that of other plants.

(*iii*) *Initial cost of the plant is very high and sometimes prohibitive.*

(*iv*) These plants cannot be necessarily located near the load centre as the same can be located at the site suitable for it.

(*v*) In this case there is more or less dependence on availability of water, which in turn depends on the natural phenomenon of rain.

Steam power stations. (*i*) The capital investment in this case as compared to hydro-electric stations is less but with the modern trend of using higher pressures for the purpose, the cost of such stations has increased considerably. But this increased cost has resulted in lower operating costs so much so that even it may compete with that of hydro-electric power stations.

(*ii*) These plants can be easily located near the load centre, as such the cost of transmission lines and the losses occurring can be minimised which results in economical operation.

(*iii*) Maintenance requirement is slightly higher.

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Fig. 8.1 shows a load duration curve.

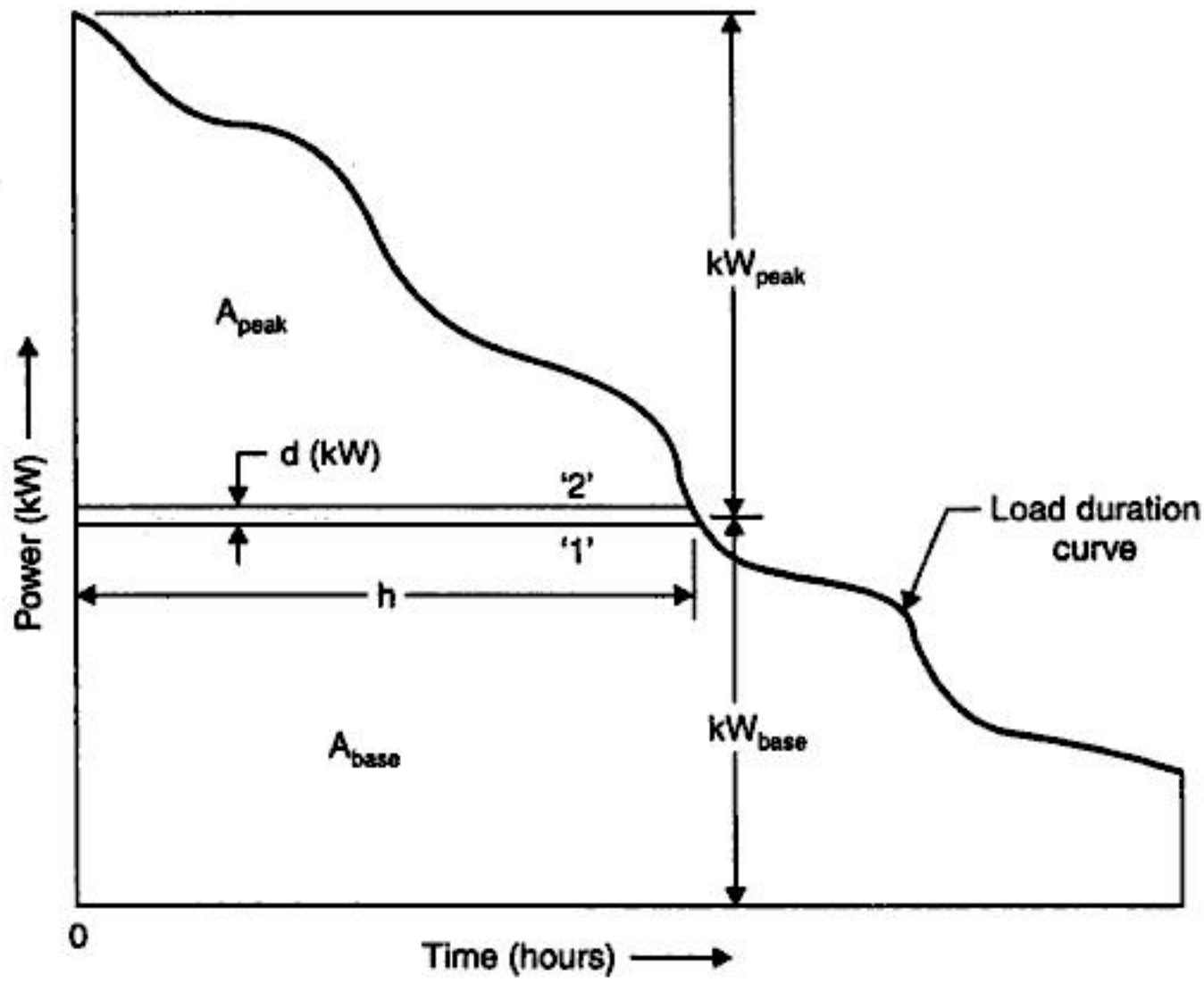

Fig. 8.1. Load duration curve of the plants.

Let, A_{peak} = Area of curve for *peak load* plant,

A_{base} = Area of curve for *base load* plant,

kW_{peak} = Load for peak load plant,

kW_{base} = Load for base load plant,

C = Total operating cost of the combination, and

h = Hours per year.

Let the *base load* be supplied by a plant having the annual cost equation as

$$(Rs.)_1 = a_1 + b_1\,kW + c_1\,kWh \qquad ...(8.1)$$

For the plant supplying the *peak load* let the equation be

$$(Rs.)_2 = a_2 + b_2\,kW + c_2\,kWh \qquad ...(8.2)$$

Since the base load plant is operated most of the time, therefore, normally a plant having $c_1 < c_2$ is used for meeting the base load.

Let $b_1 > b_2$.

Let the load between the two plants (Fig. 8.1) be divided by arbitrary line drawn on the load duration curve represented by '1'. Under these conditions let kW_{base} be the kW for base load plant and let kW_{peak} be the load for peak load plant.

In this case the total operating cost of the combination is given as :

$$C_1 = a_1 + a_2 + b_1\,kW_{base} + b_2\,kW_{peak} + c_1\,A_{base} + c_2\,A_{peak} \qquad ...(8.3)$$

Now, if the base power is extended by the amount of d (kW) to line '2', the total operating cost of the combination will modify as follows :

$$C_2 = a_1 + a_2 + b_1\,(kW_{base} + d\,kW) + b_2\,(kW_{peak} - d\,kW) + (A_{base} + d\,kW \times h)\,c_1 + (A_{peak} - d\,kW \times h)\,c_2 \qquad ...(8.4)$$

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The change in cost,

$$C_2 - C_1 = (b_1 - b_2)\, d\ \text{kW} + (c_1 - c_2)\, d\ \text{kW} \times h \qquad ...(8.5)$$

The optimum condition requirements are that above change must be zero, *i.e.*,

$$h = \frac{b_1 - b_2}{c_2 - c_1} \qquad ...(8.6)$$

Thus it is possible to divide the load between the plants due to which overall economy in operation is effected.

The method described above for distributing the load among the two power plants in an interconnected system can be used for any type of plants as (*i*) Thermal and diesel, (*ii*) Thermal and hydro, (*iii*) Nuclear and hydro and so on.

8.4. HYDRO-ELECTRIC (STORAGE TYPE) PLANT IN COMBINATION WITH STEAM PLANT

Hydro-plants can take up the load quickly and follow the peak variation much better than thermal plants. There is a great reliability in hydro-plants and it is still more in a combined system. In a combined system of hydro and thermal, water storage increases the application of more hydro-power in normal or heavy run-off years, while steam plant can help during the time of drought. *When the run-off is sufficient* (particularly in monsoon) the *hydro-plant is used as base load and thermal plant works as peak load plant. Thermal plant is used as base load plant during the drought period and hydro-plant works as peak load plant.* Fig. 8.2 (*a*), (*b*) shows their uses as base load or as peak load plant.

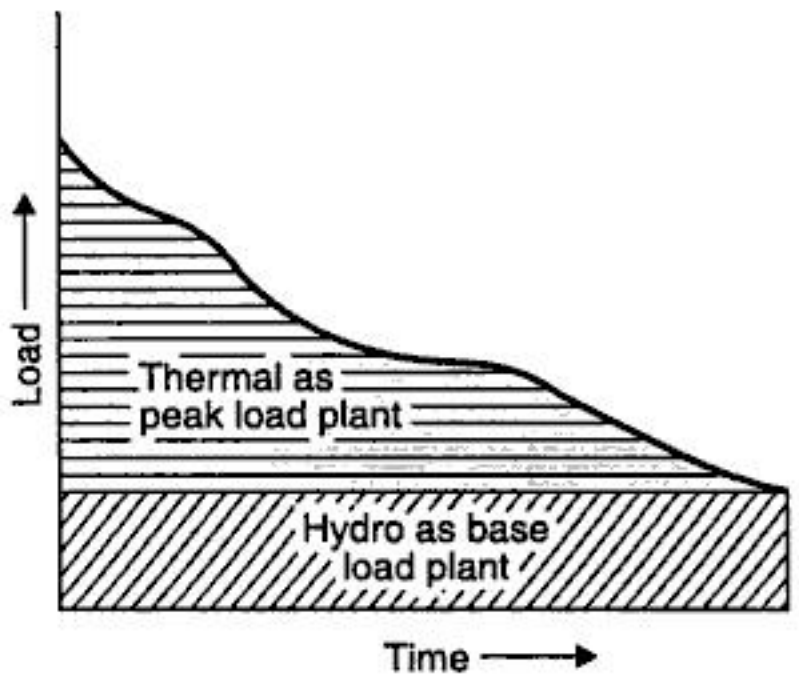

Fig. 8.2 (*a*). Hydro-plant used as base load plant during normal run-off in an inter-connected system.

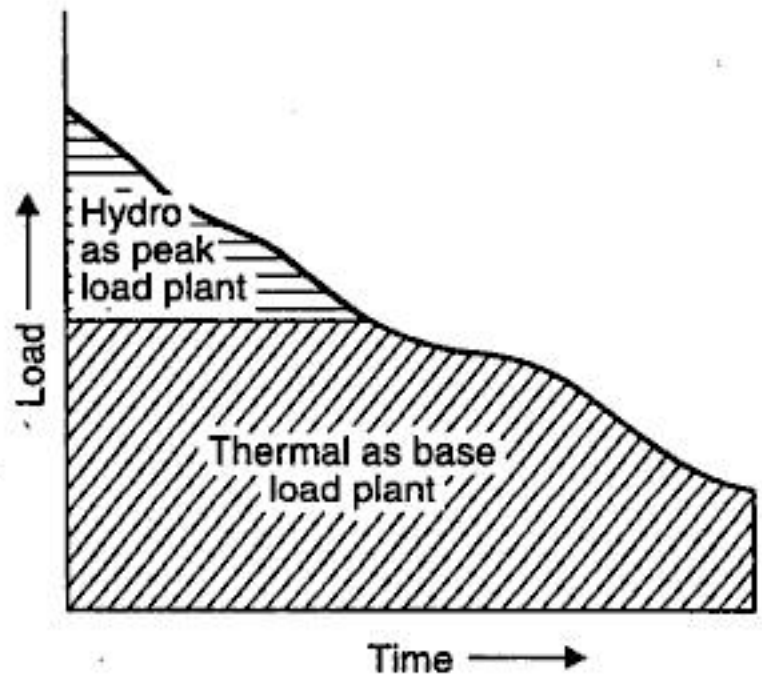

Fig. 8.2 (*b*). Hydro-plant used as peak load during drought period in an interconnected system.

Thermal plants can be used at any portion of the load duration curve but it is more expensive to use peak load station at low load factors.

Following cases will be discussed :

1. Predominant hydro.
2. Predominant thermal.
3. Hydro and thermal equally predominant.

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Predominant Hydro :

Some of the hydro-plants, such as run-off river plants, are used as base load plants whereas some others are used as peak load plants. *When the hydro-plants carry the major demand throughout the year then the thermal plants are used in a combined system to improve the hydropower efficiency during the periods when there is low run-off.*

Predominant Thermal :

To develop hydro-plants to operate even at comparatively low annual load factors is always advantageous. This is due to the fact the cost of storage water forms a major portion of the capital investment which is independent of annual load factor and capital cost is less for low than for a high load factor. Thus, *in a predominantly thermal station,* it is *preferable to develop hydro-power at the lowest practical load factor.*

Hydro and Thermal Equally Predominant :

The economic balance between hydro and thermal power in an interconnected system at any time depends upon the *nature of load curve, run-off and its seasonal variation, cost of fuel, availability of condensing water* etc. There is an optimum ratio of hydro-power to total peak demand which gives minimum cost for power supply. This is particularly true for the areas where the cost of hydro-power development is high and fuel cost is low. In areas where fuel is cheap and cost of hydro-power development is not high, the economic power ratio lies between 0.25 to 0.4. In areas where fuel is costly and favourable hydro-power plant sites are abundant the ratio will be higher to the tune of 0.8-0.9.

The combined system of hydro and thermal plants is being adopted all the world over, and is particularly useful to developing countries like India where economy is desirable at every stage of development.

8.5. RUN-OF-RIVER PLANT IN COMBINATION WITH STEAM PLANT

Since during the year the supply of water is not regular in *run-of-river plants*, therefore,these plants cannot meet with variable load requirements. Further as the variation of run-off during the year does not match the variation of power demand during the year, therefore, it becomes necessary to combine such a hydro-plant with steam plant to supply the load according to requirement with maximum reliability. *The run-of-river plant can be used as base load plant during rainy season and thermal plant takes up peak load. During dry season ; the thermal stations can be used as base load plant and run-of-river plant may work as peak load plant.*

8.6. PUMP STORAGE PLANT IN COMBINATION WITH STEAM OR NUCLEAR POWER PLANT

Whenever old and inefficient thermal stations are available they are generally used to take up peak loads. If suitable plants are not available to take load it is desirable to develop pumped storage plant for the purpose. In an interconnected system a pumped storage plant is useful in supplying sudden peak loads of short duration (a few hours in the year). Such a plant (pumped storage) possesses the following advantages when used in interconnected system :

(*i*) Thermal plants are loaded more economically.

(*ii*) The wastage of off-peak energy of thermal plants is reduced.

(*iii*) A pumped storage plant stores the energy using off-peak energy of thermal plant and the same is supplied when demand arises.

A combined system of a pumped storage plant and nuclear power plant is proposed at Ramganga power station in Uttar Pradesh. A parallel development of nuclear power station

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5. Load factor. The load factor is *the ratio of the average power to the maximum demand.* In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually *dependent upon local conditions and upon the purpose for which the load factor is to be used.* Expressing the definition mathematically,

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} \quad \ldots(9.2)$$

6. Diversity factor. The diversity factor of any system, or part of a system, *is the ratio of the maximum power demands of the subdivisions of the system, or part of a system, to the maximum demand of the whole system, or part of the system, under consideration, measured at the point of supply*. Expressing the definition mathematically,

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand of entire group}} \quad \ldots(9.3)$$

7. Utilization factor. The utilization factor is defined as *the ratio of the maximum generator demand to the generator capacity.*

8. Plant capacity factor. It is defined as the *ratio of actual energy produced in kilowatt hours (kWh) to the maximum possible energy that could have been produced during the same period.* Expressing the definition mathematically,

$$\text{Plant capacity factor} = \frac{E}{C \times t} \quad \ldots(9.4)$$

where, E = Energy produced (kWh) in a given period,

C = Capacity of the plant in kW, and

t = Total number of hours in the given period.

9. Plant use factor. It is defined as *the ratio of energy produced in a given time to the maximum possible energy that could have been produced during the actual number of hours the plant was in operation.* Expressing the definition mathematically,

$$\text{Plant use factor} = \frac{E}{C \times t'} \quad \ldots(9.5)$$

where, t' = Actual number of hours the plant has been in operation.

10. Types of loads.

(*i*) ***Residential load.*** This type of load includes domestic lights, power needed for domestic appliances such as radios, television, water heaters, refrigerators, electric cookers and small motors for pumping water.

(*ii*) ***Commercial load.*** It includes lighting for shops, advertisements and electrical appliances used in shops and restaurants etc.

(*iii*) ***Industrial load.*** It consists of load demand of various industries.

(*iv*) ***Municipal load.*** It consists of street lighting, power required for water supply and drainage purposes.

(*v*) ***Irrigation load.*** This type of load includes electrical power needed for pumps driven by electric motors to supply water to fields.

(*vi*) ***Traction load.*** It includes trams, cars, trolley, buses and railways.

11. Load curve. A load curve (or load graph) *is a graphic record showing the power demands for every instant during a certain time interval.* Such a record may cover 1 hour, in which case it would be an *hourly load graph* ; 24 hours, in which case it would be a *daily load graph* ; a month in which case it would be a *monthly load graph* ; or a year (8760 hours), in which case it would be a *yearly load graph*. The following points are worth noting :

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Refer to Fig. 9.1.

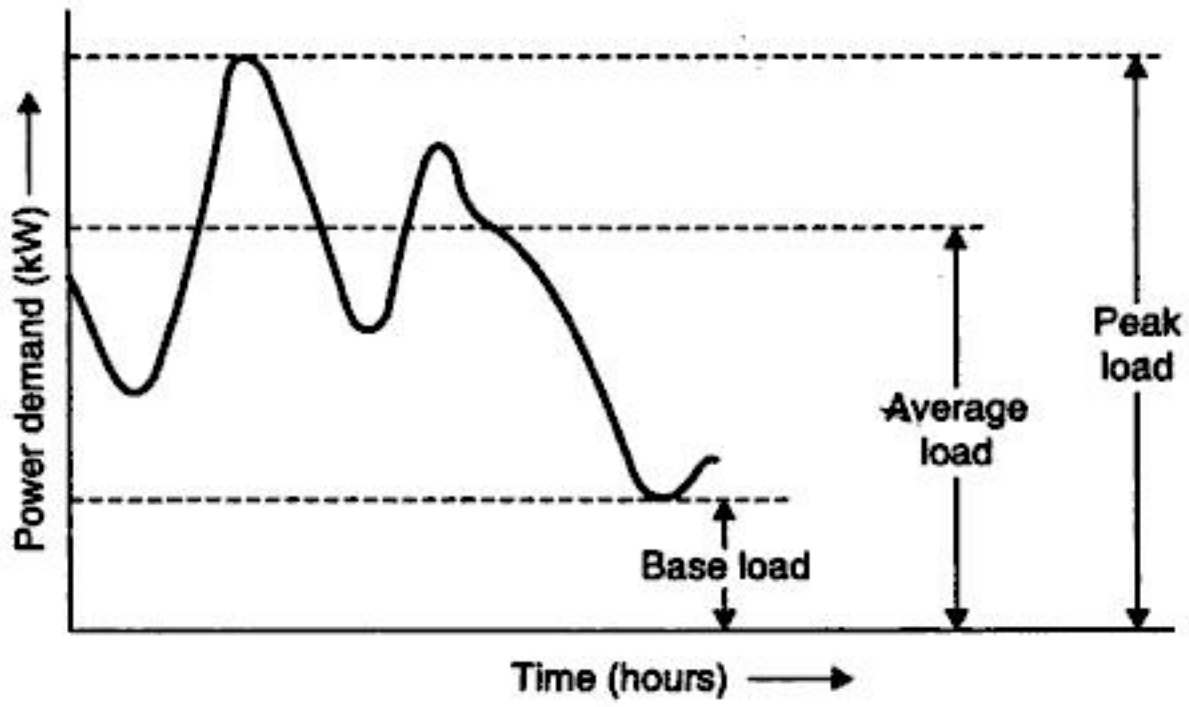

Fig. 9.1. Load curve.

(*i*) *The area under the load curve represents the energy generated in the period considered.*

(*ii*) *The area under the curve divided by the total number of hours gives the average load on the power station.*

(*iii*) *The peak load indicated by the load curve/graph represents the maximum demand of the power station.*

Significance of load curves :

- Load curves give full information about the incoming load and help to decide the installed capacity of the power station and to decide the economical sizes of various generating units.
- These curves also help to estimate the generating cost and to decide the operating schedule of the power station *i.e.*, the sequence in which different units should be run.

12. Load duration curve. A load duration curve represents re-arrangements of all the load elements of chronological load curve in order of descending magnitude. This curve is derived from the chronological load curve.

Fig. 9.2 shows a typical daily load curve for a power station. It may be observed that the maximum load on power station is 35 kW from 8 A.M to 2 P.M. This is plotted in Fig. 9.3. Similarly other loads of the load curve are plotted in *descending order* in the same figure. This is called *load duration curve* (Fig. 9.3).

The following points are worthnoting :

(*i*) *The area under the load duration curve and the corresponding chronological load curve is equal and represents total energy delivered by the generating station.*

(*ii*) *Load duration curve gives a clear analysis of generating power economically. Proper selection of base load power plants and peak load power plants becomes easier.*

13. Dump power. This term is used in hydroplants and it shows the *power in excess of the load requirements* and it is made available by *surplus water*.

14. Firm power. It is the power which *should always be available even under emergency conditions.*

15. Prime power. It is the power which may be mechanical, hydraulic or thermal that is *always available for conversion into electric power.*

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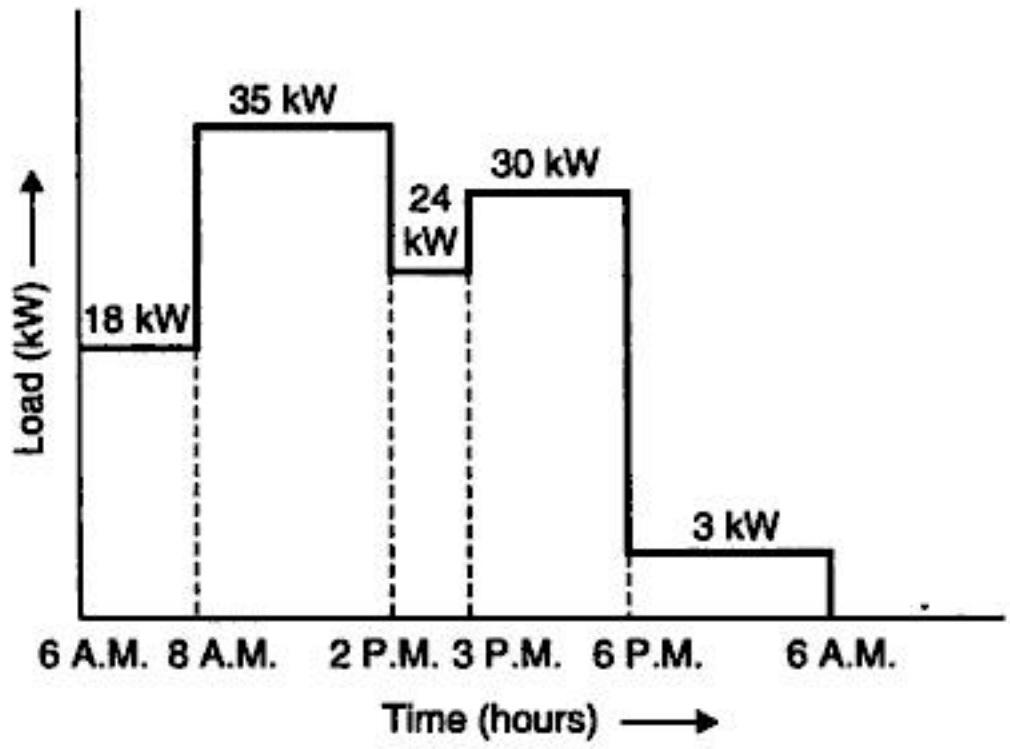

Fig. 9.2. Typical daily load curve.

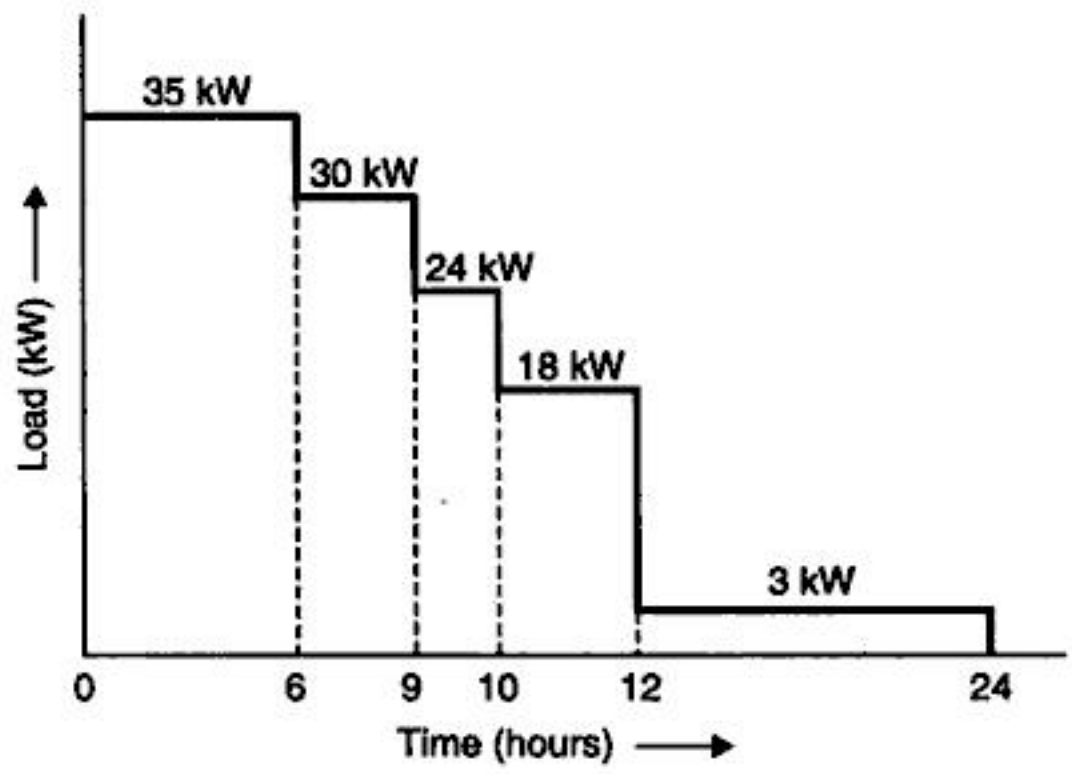

Fig. 9.3. Load duration curve.

16. Cold reserve. It is that *reserve generating capacity which is not in operation but can be made available for service.*

17. Hot reserve. It is that *reserve generating capacity which is in operation but not in service.*

18. Spinning reserve. It is that *reserve generating capacity which is connected to the bus and is ready to take the load.*

9.3. PRINCIPLES OF POWER PLANT DESIGN

The following *factors* should be considered while designing a power plant :

1. Simplicity of design.
2. Low capital cost.
3. Low cost of energy generated.
4. High efficiency.
5. Low maintenance cost.
6. Low operating cost.
7. Reliability of supplying power.
8. Reserve capacity to meet future power demand.

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9.4. LOCATION OF POWER PLANT

Some of the considerations on which the location of a power plant depends are :

1. Centre of electrical load. The plant should be located where there are industries and other important consumption places of electricity. There will be considerable *advantage* in placing the power station *nearer to the centre of the load.*

- There will be *saving in the cost of copper* used for transmitting electricity as the distance of transmission line is reduced.
- The cross-section of the transmission line directly depends upon the maximum current to be carried. In case of alternating current the voltage to be transmitted can be increased thus reducing the current and hence the *cross-section of the transmission line can be reduced.* This will *save the amount of copper.*
- It is desirable now to have a national grid connecting all power stations. This provides for selecting a site which has other advantages such as nearer to fuel supply, condensing water available.

2. Nearness to the fuel source. The cost of transportation of fuel may be quite high if the distance of location of the power plant is considerable. It may be advisable to locate big thermal power plants at the mouth of the coal mines. Lignite coal mines should have centralised thermal power station located in the mines itself as this type of coal cannot be transported. Such type of power stations could be located near oil fields if oil is to be used as a fuel and near gas wells where natural gas is available in abundance. In any case it has been seen that *it is cheaper to transmit electricity than to transport fuel.* Hence the power plant should be located nearer the fuel supply source.

3. Availability of water. The availability of water is of greater importance than all other factors governing station location. Water is required for a thermal power station using turbines for the following two purposes :

(*i*) To supply the make-up water which should be reasonably pure water.

(*ii*) To cool the exhaust steam. This cooling process is done in case of diesel engines too. For *bigger power stations* the quantity of this cooling water is tremendous and requires *some natural source of water* such as *lake, river or even sea.* Cooling towers could be used economically as the same cooling water could be used again and again. Only a part of make-up water for cooling will then be required. For *small plants spray pounds* could sometimes be used. *It is economical to limit the rise in cooling-water temperature to a small value (between 6°C and 12°C), and to gain in cycle efficiency at the expense of increased cooling water pumping requirement.*

4. Type of soil available and land cost. While selecting a site for a power plant it is important to know about the character of the soil. If the soil is loose having low bearing power the pile foundations have to be used. Boring should be made at most of the projected site to have an idea of the character of the various strata as well as of the bearing power of the soil. *The best location is that for which costly and special foundation is not required.*

In case of power plants being situated near metropolitan load centres, the land there will be very costly as compared to the land at a distance from the city.

9.5. LAYOUT OF POWER PLANT BUILDING

The following points should be taken care of while deciding about power *plant building and its layout :*

1. The power plant structure should be simple and rugged with pleasing appearance.
2. Costly materials and ornamental work should be avoided.

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3. The power plant interior should be clean, airy and attractive.

4. The exterior of the building should be impressive and attractive.

5. Generally the building should be *single storeyed*.

6. The layout of the power plant should first be made on paper, the necessary equipment well arranged and then design the covering structure. In all layout, allowances must be made for sufficient clearances and for walkways. Good clearance should be allowed around generators, boilers, heaters, condensers etc. Walkway clearances around hot objects and rapidly moving machinery should be wider than those just necessary to allow passage. Also the galleries in the neighbourhood of high tension bus bars should be sufficient as the space will permit.

7. Provision for future extension of the building should be made.

8. The height of the building should be sufficient so that overhead cranes could operate well and the overhauling of the turbines etc. is no problem. Sufficient room should be provided to lift the massive parts of the machines.

9. Each wall should receive a symmetrical treatment in window openings etc.

10. The principal materials used for building the power plant building are brick, stone, hollow tiles, concrete and steel.

11. In case of a *steam power plant*, there are distinct parts of the building *viz., boiler room, turbine room* and *electrical bays*. Head room required in the boiler room should be greater than in the others. Ventilation in boiler room presents greater difficulty because of heat liberated from the boiler surfaces. The turbine room is actually the show room of the plant. Mezzanine flooring should be used in the power plant. The chimney height should be sufficient so as to release the flue gases sufficiently high so that the atmosphere is not polluted and the nearby buildings are not affected.

12. The foundation of a power plant is one of the most important considerations. For this the bearing capacity of the sub-soil, selection of a working factor of safety and proportioning the wall footings to economical construction should be well thought of and tested. The pile foundations may have to be used where the soils have low bearing values.

13. In any power plant *machine foundation* plays an important part. The machine foundation should be able to distribute the weight of the machine, bed plate and its own weight over a safe subsoil area. It must also provide sufficient mass *to absorb machine vibrations*.

14. Sufficient room for storage of fuel should be provided indoor as well as outdoor so as to ensure against any prolonged breakdown.

9.6. COST ANALYSIS

The cost of a power system depends upon whether :

(*i*) an entirely new power system has to be set up, or

(*ii*) an existing system has to be replaced, or

(*iii*) an extension has to be provided to the existing system. The cost interalia includes :

1. Capital Cost or Fixed Cost. It includes the following :

(*i*) Initial cost (*ii*) Interest

(*iii*) Depreciation cost (*iv*) Taxes

(*v*) Insurance.

2. Operational Cost. It includes the following :

(*i*) Fuel cost (*ii*) Operating labour cost

(*iii*) Maintenance cost (*iv*) Supplies

(*v*) Supervision (*vi*) Operating taxes.

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The above mentioned costs are discussed as follows :

(*a*) Initial Cost :

Some of the several factors on which cost of a generating station or a power plant depends are :

(*i*) Location of the plant. (*ii*) Time of construction.

(*iii*) Size of units. (*iv*) Number of main generating units.

(*v*) The type of structure to be used.

The *initial cost* of a power station includes the following :

1. Land cost. 2. Building cost.
3. Equipment cost. 4. Installation cost.
5. Overhead charges which will include the transportation cost, stores and storekeeping charges, interest during construction etc.

— To *reduce the cost of building*, it is desirable to eliminate the superstructure over the boiler house and as far as possible on turbine house also.

— The *cost on equipment can be reduced* by adopting unit system where one boiler is used for one turbogenerator. Also by simplifying the piping system and elimination of duplicate system such as steam headers and boiler feed headers. The cost can be further reduced by eliminating duplicate or stand-by auxiliaries.

— When the power plant is not situated in the proximity to the load served, the cost of a primary distribution system will be a part of the initial investment.

(*b*) Interest :

All enterprises need investment of money and this money may be obtained as loan, through bonds and shares or from owners of personal funds. *Interest is the difference between money borrowed and money returned*. It may be charged at a simple rate expressed as % per annum or may be compounded, in which case the interest is reinvested and adds to the principal, thereby earning more interest in subsequent years. Even if the owner invests his own capital the charge of interest is necessary to cover the income that he would have derived from it through an alternative investment or fixed deposit with a bank. *Amortization* in the periodic repayment of the principal as a uniform annual expense.

(*c*) Depreciation :

Depreciation accounts for the deterioration of the equipment and decrease in its value due to corrosion, weathering and wear and tear with use. It also covers the decrease in value of equipment due to obsolescence. With rapid improvements in design and construction of plants, obsolescence factor is of enormous importance. Availability of better models with lesser overall cost of generation makes it imperative to replace the old equipment earlier than its useful life is spent. The actual life span of the plant has, therefore, to be taken as shorter than what would be normally expected out of it.

The following methods are used to calculate the depreciation cost :

(*i*) Straight line method. (*ii*) Percentage method.

(*iii*) Sinking fund method. (*iv*) Unit method.

(*i*) **Straight line method.** It is the *simplest* and *commonly used method*. The life of the equipment or the enterprise is first assessed as also the residual or salvage value of the same after the estimated life span. This salvage value is *deducted* from the initial capital cost and the balance is *divided by the life as assessed in years*. Thus, the annual value of decrease in cost of equipment is found and is set aside as depreciation annually from the income. *Thus, the rate of depreciation is uniform throughout the life of the equipment*. By the time the equipment has lived out its useful life,

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an amount equivalent to its net cost is accumulated which can be utilised for replacement of the plant.

(*ii*) **Percentage method.** In this method the deterioration in value of equipment from year to year is taken into account and the amount of depreciation calculated upon actual residual value for each year. It thus, reduces for successive years.

(*iii*) **Sinking fund method.** This method is based on the *conception that the annual uniform deduction from income for depreciation will accumulate to the capital value of the plant at the end of life of the plant or equipment.* In this method, the amount set aside per year consists of annual instalments and the interest earned on all the instalments.

Let, A = Amount set aside at the end of each year for n years,
n = Life of plant in years,
S = Salvage value at the end of plant life,
i = Annual rate of compound interest on the invested capital, and
P = Initial investment to install the plant.

Then, amount set aside at the end of first year = A

Amount at the end of second year

$$= A + \text{interest on } A = A + Ai = A(1 + i)$$

Amount at the end of third year

$$= A(1 + i) + \text{interest on } A(1 + i)$$
$$= A(1 + i) + A(1 + i)i$$
$$= A(1 + i)^2$$

$\therefore$ Amount at the end of nth year $= A(1 + i)^{n-1}$

Total amount accumulated in n years (say x)

= Sum of the amounts accumulated in n years

i.e.,
$$x = A + A(1 + i) + A(1 + i)^2 + \ldots\ldots + A(1 + i)^{n-1}$$
$$= A\,[1 + (1 + i) + (1 + i)^2 + \ldots\ldots + (1 + i)^{n-1}] \quad \ldots(i)$$

Multiplying the above equation by $(1 + i)$, we get

$$x(1 + i) = A\,[(1 + i) + (1 + i)^2 + (1 + i)^3 + \ldots\ldots + (1 + i)^n] \quad \ldots(ii)$$

Subtracting equation (i) from (ii), we get

$$x.i = [(1 + i)^n - 1]\,A$$

$\therefore$
$$x = \left[\frac{(1+i)^n - 1}{i}\right] A$$

where, $x = (P - S)$

$\therefore$
$$P - S = \left[\frac{(1+i)^n - 1}{i}\right] A \quad \ldots(9.6)$$

or,
$$A = \left[\frac{i}{(1+i)^n - 1}\right] (P - S) \quad \ldots(9.7)$$

(*iv*) **Unit method.** In this method *some factor is taken as a standard one and depreciation is measured by that standard.* In place of years an equipment will last, the number of hours that an equipment will last is calculated. This total number of hours is then divided by the capital value of the equipment. This constant is then multiplied by the number of actual working hours each year to get the value of depreciation for that year. In place of number of hours, the number of units of production is taken as the measuring standard.

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(*d*) **Operational cost :**

The elements that make up the operating expenditure of a power plant include the following costs :

(*i*) Cost of fuels. (*ii*) Labour cost.

(*iii*) Cost of maintenance and repairs. (*iv*) Cost of stores (other than fuel).

(*v*) Supervision. (*vi*) Taxes.

(*i*) ***Cost of fuels.*** In a thermal station fuel is the heaviest item of operating cost. The selection of the fuel and the maximum economy in its use are, therefore, very important considerations in thermal plant design. It is desirable to achieve the highest thermal efficiency for the plant so that fuel charges are reduced. *The cost of fuel includes not only its price at the site of purchase but its transportation and handling costs also.* In the hydroplants the absence of fuel factor in cost is responsible for lowering the operating cost. *Plant heat rate can be improved by the use of better quality of fuel or by employing better thermodynamic conditions in the plant design.*

The cost of fuel varies with the following :

- Unit price of the fuel.
- Amount of energy produced.
- Efficiency of the plant.

(*ii*) ***Labour cost.*** For plant operation labour cost is another item of operating cost. Maximum labour is needed in a thermal power plant using coal as a fuel. A hydraulic power plant or a diesel power plant of equal capacity require a lesser number of persons. In case of automatic power station the cost of labour is reduced to a great extent. However labour cost cannot be completely eliminated even with fully automatic station as they will still require some manpower for periodic inspection etc.

(*iii*) ***Cost of maintenance and repairs.*** In order to avoid plant breakdowns *maintenance* is necessary. *Maintenance* includes *periodic cleaning, greasing, adjustments and overhauling of equipment*. The material used for maintenance is also charged under this head. Sometimes an arbitrary percentage is assumed as maintenance cost. A good plan of maintenance would keep the sets in dependable condition and avoid the necessity of too many stand-by plants.

Repairs are necessitated when the plant breaks down or stops due to faults developing in the mechanisms. The repairs may be minor, major or periodic overhauls and are charged to the depreciation fund of the equipment. This item of cost is higher for thermal plants than for hydro-plants due to complex nature of principal equipment and auxiliaries in the former.

(*iv*) ***Cost of stores*** (other than fuel). The items of consumable stores other than fuel include such articles as lubricating oil and greases, cotton waste, small tools, chemicals, paints and such other things. The incidence of this cost is also higher in thermal stations than in hydro-electric power stations.

(*v*) ***Supervision.*** In this head the salary of supervising staff is included. A good supervision is reflected in lesser breakdowns and extended plant life. The supervising staff includes the station superintendent, chief engineer, chemist, engineers, supervisors, stores incharges, purchase officer and other establishment. Again, thermal stations, particularly coal fed, have a greater incidence of this cost than the hydro-electric power stations.

Taxes. The taxes under operating head includes the following :

(*i*) Income tax

(*ii*) Sales tax

(*iii*) Social security and employee's security etc.

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9.7. SELECTION OF TYPE OF GENERATION

While choosing the type of generation the following points should be taken into consideration :

1. The type of fuel available or availability of suitable sites for water power generation.
2. Fuel transportation cost.
3. Land required.
4. Foundation cost.
5. The availability of cooling water.
6. The type of load to be taken by the power plant.
7. Reliability in operation.
8. Plant life.
9. Cost of transmitting the energy.

9.8. SELECTION OF POWER PLANT EQUIPMENT

Selection of some important power plant equipment is discussed below :

9.8.1. Selection of Boilers

It is now well known fact that only water tube boilers (fire tube boilers not suitable) should be used for all central power stations. While selecting a boiler the following points should be taken care of :

1. Type of fuel to be burnt.
2. Type of load.
3. Cost of fuel.
4. Desirability of heat-reclaiming equipment.
5. Availability of space for boiler installation.

- The design and efficiency of the boiler is considerably influenced by the *type of fuel* used in a boiler. *A high efficiency can be obtained with coal firing as compared to oil or gas firing.* This is due to increased hydrogen loss in gaseous fuels.
- *The location of the plant* will also decide the type of fuel to be used. If the plant is nearer the coal fields, coal will be cheaper. Power plants near to the oil fields and gas wells will naturally use these fuels.
- *Coal firing* will also *influence furnace design and hence the cost of boiler.* In case of low ranking fuel such as lignites etc., pulverised firing is used. Very low fusing temperatures of coal require water-cooled walls and in some cases the slag tap furnaces. The yearly minimum operating cost has to be considered which may include production cost and fixed charges. In case of anthracite coal or metallurgical coke etc. the wear on pulverising machinery is relatively much higher than that of bituminous coal.

The cost of boilers vary with the following :

(*i*) Type of boiler used.
(*ii*) Operating pressure.
(*iii*) Operating temperature.
(*iv*) Type of firing.
(*v*) Efficiency desired.

- '*Heat-reclaiming equipment*' such as *economisers* and *air preheaters* should be provided with boilers. With the addition of economisers and air preheaters the efficiency of the boiler increases from 75% to 90% and above.

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Total annual cost = Rs. $(0.5 + 7 + 1 + 1.2 + 0.2 + 52.5) \times 10^6$ = Rs. 62.4×10^6

Total energy generated per annum

= Maximum demand × average load factor × (365 × 24)

= $200000 \times 0.6 \times (365 \times 24) = 1051.2 \times 10^6$ kWh

Cost of generation $= \dfrac{\text{Total annual cost}}{\text{Total units generated}}$

$= \dfrac{62.4 \times 10^6}{1051.2 \times 10^6}$ **= Rs. 0.0594 per kWh or 5.94 p. per kWh. (Ans.)**

If the load factor is improved to 75% :

Total energy generated per annum

= $200000 \times 0.75 \times (365 \times 24) = 1314 \times 10^6$ kWh

Annual operating cost = Rs. $(0.5 + 7 \times 1.1 \times 10^6 + 1 + 1.2 + 0.2 + 52.5) \times 10^6$

= Rs. 63.1×10^6

Cost of generation $= \dfrac{\text{Total annual cost}}{\text{Total units generated}}$

$= \dfrac{63.1 \times 10^6}{1314 \times 10^6}$ **= Rs. 0.048 per kWh or 4.8 p. per kWh. (Ans.)**

Example 9.19. *A steam station has two 110 MW units. Following cost data are given :*

Particulars	*Units A*	*Units B*
Capital cost	*Rs. 2400 per kW*	*Rs. 3000 per kW*
Fixed charge rate	*10%*	*10%*
Capital factor	*0.55*	*0.60*
Fuel consumption	*1 kg/kWh*	*0.9 kg/kWh*
Fuel cost	*Rs. 96 per 1000 kg*	*Rs. 96 per 1000 kg*
Annual cost of operation, labour, maintenance and supplies	*20% of annual fuel cost*	*15% of annual fuel cost*
Utilisation factor	*1*	*1*

Calculate the following :

(i) Annual plant cost and generation cost of unit A.

(ii) Annual plant cost and generation cost of unit B.

(iii) Overall generation cost of the station.

Solution. (i) Annual plant cost and generation cost of unit A :

Annual fixed cost of unit A

$= \dfrac{10}{100} \times 2400 \times (100 \times 1000)$

= Rs. 26.4×10^6

Annual energy output = Maximum demand × capacity factor × no. of hours

= $(100 \times 1000) \times 0.55 \times (356 \times 24)$

= 52.998×10^7 kWh

Annual fuel consumption = $1 \times 52.998 \times 10^7$

= 52.998×10^7 kg

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Fuel cost $= \frac{96}{1000} \times 52.998 \times 10^7 = \text{Rs. } 50.87 \times 10^7$

Annual cost of operating labour, maintenance and supplies

$= 20\%$ of annual cost

$= \frac{20}{100} \times 50.87 \times 10^6 = \text{Rs. } 10.174 \times 10^6$

The annual operating cost of unit A

= Annual fuel cost + annual cost of operation, labour and maintenance

$= \text{Rs. } (50.87 \times 10^6 + 10.174 \times 10^6) = \text{Rs. } 61.044 \times 10^6$

Annual plant cost of unit A

= Annual fixed cost + annual operating cost

$= \text{Rs. } (26.4 \times 10^6 + 61.044 \times 10^6) = \mathbf{Rs.\ 87.444 \times 10^6.}$ **(Ans.)**

Generation cost of unit A

$$= \frac{\text{Annual plant cost}}{\text{Annual energy output}}$$

$$= \frac{87.444 \times 10^6}{52.998 \times 10^7} = \textbf{Rs. 0.165 or 16.5 p/kWh. (Ans.)}$$

(*ii*) **Annual plant cost and generation cost of unit B :**

Annual fixed cost of unit B

$= \text{Rs. } \frac{10}{100} \times 3000 \times 110 \times 1000 = \text{Rs. } 33 \times 10^6$

Expected annual energy output

$= (110 \times 1000) \times (365 \times 24) \times 0.6 = 57.816 \times 10^7$ kWh

Annual fuel consumption

$= 0.9 \times 57.816 \times 10^7 = 52.0344 \times 10^7$ kg

Fuel cost $= \frac{96}{100} \times 52.0344 \times 10^7 = \text{Rs. } 49.95 \times 10^6$

Annual cost of maintenance, repair etc.

$= \text{Rs. } \frac{15}{100} \times 49.95 \times 10^6 = \text{Rs. } 7.4925 \times 10^6$

Annual operating cost

= Fuel cost + maintenance cost

$= \text{Rs. } (49.95 \times 10^6 + 7.4925 \times 10^6) = \text{Rs. } 57.4425 \times 10^6$

Annual plant cost of unit B

= Fixed cost + operating cost

$= \text{Rs. } 33 \times 10^6 + 57.4425 \times 10^6$

$= \mathbf{Rs.\ 90.4425 \times 10^6.}$ **(Ans.)**

Generation cost of unit B

$$= \frac{\text{Annual plant cost}}{\text{Annual energy output}}$$

$$= \frac{90.4425 \times 10^6}{57.816 \times 10^7}$$

$= \textbf{Rs. 0.1564 or 15.64 p/kWh. (Ans.)}$

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(*iii*) **Overall generation cost of the station**

$$= \frac{\text{Sum of annual plant cost of both units}}{\text{Sum of energy supplied}}$$

$$= \frac{87.444 \times 10^6 + 90.4425 \times 10^6}{52.998 \times 10^7 + 57.816 \times 10^7}$$

= Rs. 0.16 or 16 p/kWh. (Ans.)

☞**Example 9.20.** *The annual costs of operating a 15000 kW thermal power station are as follows :*

Cost of plant	*= Rs. 1080 per kW*
Interest, insurance, taxes on plant	*= 5 per cent*
Depreciation	*= 5 per cent*
Cost of primary distribution system	*= Rs. 600000*
Interest, insurance, taxes and depreciation on primary distribution system	*= 5 per cent*
Cost of secondary distribution system	*= Rs. 1080000*
Interest, taxes, insurance and depreciation on secondary distribution system	*= 5 per cent*
Maintenance of secondary distribution system	*= Rs. 216000*
Plant maintenance cost	
(i) Fixed cost	*= Rs. 36000*
(ii) Variable cost	*= Rs. 48000*
Operating costs	*= Rs. 720000*
Cost of coal	*= Rs. 7.2 per kN*
Consumption of coal	*= 300000 kN*
Dividend to stock holders	*= Rs. 1200000*
Energy loss in transmission	*= 10 per cent*
Maximum demand	*= 14000 kW*
Diversity factor	*= 1.5*
Load factor	*= 0.7*

Determine : (i) Charge per kW per year

(ii) Rate per kWh.

Solution. Maximum demand = 14000 kW

$$\text{Load factor} = 0.7 = \frac{\text{Average load}}{\text{Maximum demand}}$$

$\therefore$ Average load $= 0.7 \times 14000 = 9800$ kW

$\therefore$ Energy generated per year $= 9800 \times (365 \times 24)$

$= 85.8 \times 10^6$ kWh

Cost of plant = Capacity of plant × cost per kW

$= 15000 \times 1080 = \text{Rs. } 16.2 \times 10^6$

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☞**Example 9.34.** *A load having a maximum demand of 100 MW and a load factor of 0.4 may be supplied by one of the following schemes :*

(i) A steam station capable of supplying the whole load.

(ii) A steam station in conjunction with pump storage plant which is capable of supplying 130×10^6 kWh energy per year with a maximum output of 40 MW.

Find out the cost of energy per unit in each of the two cases mentioned above.

Use the following data :

Capital cost of steam station = *Rs. 2000/kW of installed capacity*

Capital cost of pump storage plant = *Rs. 1300/kW of installed capacity*

Operating cost of steam plant = *6 p./kWh*

Operating cost of pump storage plant = *0.5 p./kWh*

Interest and depreciation together on the capital invested should be taken as 12 per cent. Assume that no spare capacity is required.

Solution. (*i*) **Steam station :**

Capital cost $= 100 \times 10^3 \times 2000 = \text{Rs. } 200 \times 10^6$

Interest and depreciation $= \frac{12}{100} \times 200 \times 10^6 = \text{Rs. } 24 \times 10^6$

Average load = Load factor × maximum demand

$= 0.4 \times 100 \times 10^3 = 40000$ kW

Energy supplied per year = Average load × (365 × 24)

$= 40000 \times 365 \times 24 = 350.4 \times 10^6$ kWh

∴ Interest and depreciation charges *per unit of energy*

$$= \frac{24 \times 10^6}{350.4 \times 10^6} \times 100 = 6.85 \text{ p/kWh}$$

∴ *Total cost per unit* $= 6 + 6.85 =$ **12.85 p/kWh. (Ans.)**

(*ii*) **Steam station in conjunction with pump-storage plant :**

The load supplied by the steam plant $= 100 - 40 = 60$ MW

∴ Capital cost of steam plant $= 60 \times 1000 \times 2000 = \text{Rs. } 120 \times 10^6$

Capital cost of pump storage plant $= 40 \times 1000 \times 1300 = \text{Rs. } 52 \times 10^6$

∴ Total capital cost of combined station $= 120 \times 10^6 + 52 \times 10^6 = \text{Rs. } 172 \times 10^6$

Interest and depreciation charges on capital investment

$$= \frac{12}{100} \times 172 \times 10^6 = \text{Rs. } 20.64 \times 10^6$$

∴ Operating cost of pump storage plant $= \frac{0.5}{100} \times 130 \times 10^6 = \text{Rs. } 0.65 \times 10^6$

The energy units supplied by steam station

= Total units required – energy units supplied by pump storage plant

$= 350.4 \times 10^6 - 130 \times 10^6 = 220.4 \times 10^6$ kWh

Operating cost of the steam station

$$= \frac{6}{100} \times 220.4 \times 10^6 = \text{Rs. } 13.22 \times 10^6$$

Total cost per year $= \text{Rs. } (20.64 \times 10^6 + 0.65 \times 10^6 + 13.22 \times 10^6) = \text{Rs. } 34.51 \times 10^6$

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$$\textit{Total cost per unit} = \frac{34.51 \times 10^6}{350.4 \times 10^6} \times 100 = \textbf{9.85 p/kWh.} \quad \textbf{(Ans.)}$$

Note : If the above example is repeated with a load factor of 0.7 it will be observed from the results that the *cost of generation becomes less with higher load factor irrespective of the type of the plant.*

Example 9.35. *The following data relate to a 2000 kW diesel power station :*

The peak load on the plant = *1500 kW*
Load factor = *0.4*
Capital cost per kW installed = *Rs. 1200*
Annual costs = *15 per cent of capital*
Annual operating costs = *Rs. 50000*
Annual maintenance costs :
(i) Fixed = *Rs. 9000*
(ii) Variable = *Rs. 18000*
Cost of fuel = *Rs. 0.45 per kg*
Cost of lubricating oil = *Rs. 1.3 per kg*
C.V. of fuel = *41800 kJ/kg*
Consumption of fuel = *0.45 kg/kWh*
Consumption of lubricating oil = *0.002 kg/kWh*
Determine the following :
(i) The annual energy generated.
(ii) The cost of generation per kWh.

Solution. Capital cost of the plant = $2000 \times 1200 = \text{Rs. } 2.4 \times 10^6$ per year

Interest on capital = $\frac{15}{100} \times 2.4 \times 10^6 = \text{Re. } 0.36 \times 10^6$ per year.

(*i*) **Annual energy generated** = Load factor × maximum demand × (365 × 24)
= $0.4 \times 1500 \times 365 \times 24 = \mathbf{5.256 \times 10^6\ kWh.}$ **(Ans.)**

(*ii*) **Cost of generation :**

Fuel consumption = $0.45 \times 5.256 \times 10^6 = 2.365 \times 10^6$ kg per year
Cost of fuel = Rs. $0.45 \times 2.365 \times 10^6 = \text{Rs. } 1.064 \times 10^6$ per year
Lubricant consumption = $0.002 \times 5.256 \times 10^6 = 10512$ kg per year
Cost of lubricating oil = $1.3 \times 10512 = \text{Rs. } 13665$ per year
Total fixed cost = Interest + maintenance (fixed)
= $0.36 \times 10^6 + 9000 = \text{Rs. } 369000$ per year

Total running or variable costs
= Fuel cost + lubricant cost + maintenance (running) + annual operating costs
= $1.064 \times 10^6 + 13665 + 18000 + 50000 = \text{Rs. } 1145665$ per year
Total cost = Fixed cost + running cost = $369000 + 1145665 = \text{Rs. } 1514665$

$$\textit{Cost of generation} = \frac{1514665}{5.256 \times 10^6} \times 100 = \textbf{28.8 paise/kWh.} \quad \textbf{(Ans.)}$$

☞**Example 9.36.** *The annual costs of operating a 15 MW thermal plant are given below :*

Capital cost of plant = *Rs. 1500/kW*
Interest, insurance and depreciation = *10 per cent of plant cost*

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Capital cost of primary and secondary distribution = *Rs.* 20×10^6
Interest, insurance and depreciation on the capital cost of primary and secondary distribution = *5% the capital cost*
Plant maintenance cost = *Rs.* 100×10^3 *per year*
Maintenance cost of primary and secondary equipment = *Rs.* 2.2×10^5 *per year*
Salaries and wages = *Rs.* 6.5×10^5 *per year*
Consumption of coal = 40×10^4 *kN per year*
Cost of coal = *Rs. 9 per kN*
Dividend to stockholders = *Rs.* 1.5×10^6 *per year*
Energy loss in transmission = *10 per cent*
Diversity factor = *1.5*
Load factor = *0.75*
Maximum demand = *12 MW*

(*i*) *Devise a two-part tariff.*
(*ii*) *Find the average cost per kWh.*

Solution. (*i*) **Two-part tariff :**

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$\therefore$ Average load = Load factor × maximum demand
$= 0.75 \times 12 \times 10^3 = 9000$ kW

Energy generated per year $= 9000 \times (365 \times 24) = 78.84 \times 10^6$ kWh
Cost of the plant $= 15 \times 10^3 \times 1500 = \text{Rs. } 22.5 \times 10^6$
Interest, insurance and depreciation charges of the plant

$$= \frac{10}{100} \times 22.5 \times 10^6 = \text{Rs. } 2.25 \times 10^6$$

Interest, insurance and depreciation charges of primary and secondary equipments

$$= \frac{5}{100} \times 20 \times 10^6 = \text{Rs. } 1.0 \times 10^6$$

Total fixed cost = Insurance, interest and depreciation costs + dividend to stock-holders
$= \text{Rs. } (2.25 \times 10^6 + 1.5 \times 10^6) = \text{Rs. } 3.75 \times 10^6$

Sum of individual maximum demand
= Maximum demand × diversity factor
$= 12 \times 10^3 \times 1.5 = 18000$ kW

$\therefore$ *Fixed charges per kW* $= \dfrac{3.75 \times 10^6}{18000} =$ **Rs. 208.3.**

Total variable charges = All maintenance costs + salaries and wages + fuel cost
$= (100 \times 10^3 + 2.2 \times 10^5) + 6.5 \times 10^5 + 40 \times 10^4 \times 9$
$= (1 \times 10^5 + 2.2 \times 10^5) + 6.5 \times 10^5 + 36 \times 10^5$
$= \text{Rs. } 45.7 \times 10^5 \text{ or Rs. } 4.57 \times 10^6$

Energy transmitted = Energy generated × transmission efficiency

$$= 78.84 \times 10^6 \times \left(\frac{100 - \text{energy loss in transmission}}{100}\right)$$

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$$= 78.84 \times 10^6 \times \frac{90}{100} = 70.956 \times 10^6 \text{ kWh}$$

$\therefore$ *Charges for energy consumption*

$$= \frac{4.57 \times 10^6}{70.956 \times 10^6} \times 100 = \textbf{6.44 paise/kWh.}$$

$\therefore$ *Two-part tariff* = **Rs. 208.3/kW + 6.44 paise/kWh. (Ans.)**

(*ii*) **Average cost per kWh :**

Total charges = Fixed charges + variable charges

$= 3.75 \times 10^6 + 4.57 \times 10^6 = \text{Rs. } 8.32 \times 10^6$

Average cost of supply $= \frac{8.32 \times 10^6}{70.956 \times 10^6} \times 100 =$ **11.72 paise/kWh. (Ans.)**

Example 9.37. *A 10 MW thermal power plant has the following data :*

Peak load = *8 MW*

Plant annual load factor = *0.72*

Cost of the plant = *Rs. 800 / kW installed capacity*

Interest, insurance and depreciation = *10 per cent of the capital cost*

Cost of transmission and distribution system = *Rs. 350 × 10³*

Interest, depreciation on distribution system = *5 per cent*

Operating cost = *Rs. 350 × 10³ per year*

Cost of coal = *Rs. 6 per kN*

Plant maintenance cost = *Rs. 30000 / year (fixed)*

= *Rs. 40000 / year (running)*

Coal used = *250000 kN / year*

Assume transmission and distribution costs are to be charged to generation

(i) Devise a two-part tariff.

(ii) Average cost of generation in paise / kWh.

Solution. (*i*) **Two-part tariff :**

S. No.	*Items*	*Fixed cost per year (in Rs.)*	*Running cost per year (in Rs.)*
1.	Interest, depreciation etc. of the plant	$\frac{10}{100} \times 10000 \times 800$ $= \text{Rs. } 800 \times 10^3$	—
2.	Interest, depreciation etc. of the transmission and distribution	$\frac{5}{100} \times 350 \times 10^3$ $= 17.5 \times 10^3$	—
3.	Annual cost of coal	—	250000×6 $= 1500 \times 10^3$
4.	Operating cost	—	$= 350 \times 10^3$
5.	Plant maintenance cost	$= 30 \times 10^3$	$= 40 \times 10^3$
	Total cost	847.5×10^3	1890×10^3

$\therefore$ Grand total cost = Fixed cost + running cost

$= 847.5 \times 10^3 + 1890 \times 10^3 = \text{Rs. } 2737.5 \times 10^3$

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10. The daily load curve of a power plant is given by the table below :

Time :	12	2	4	6	8	10	12	2	4	6	8	10	12
Load (MW) :	2	2.5	3	4	6	6.5	6.5	5	6	8	9	5	2

(*i*) Find the daily load factor.

(*ii*) All loads in excess of 400 kW are carried out by unit No. 2 rated at 600 kW. Find its use factor.

[**Ans.** (*i*) 0.814 (*ii*) 0.417]

11. The annual peak load on a 30 MW power station is 25 MW. The power station supplies load having maximum demands of 10 MW, 8.5 MW, 5 MW and 4.5 MW. The annual load factor is 0.45. Find :

(*i*) Average load (*ii*) Energy supplied per year

(*iii* Diversity factor (*iv*) Demand factor.

[**Ans.** (*i*) 11.25 MW (*ii*) 98.55 × 10^6 kWh (*iii*) 1.12 (*iv*) 0.9]

12. A generating station supplies the following loads :

15 MW, 12 MW, 8.5 MW, 6 MW and 0.45 MW. The station has a maximum demand of 22 MW. The annual load factor of the station is 0.48. Calculate :

(*i*) The number of units supplied annually

(*ii*) The diversity factor. (*iii*) The demand factor.

[**Ans.** (*i*) 92.5 × 10^6 kWh (*ii*) 1.907 (*iii*) 0.525]

13. A power station has a maximum demand of 15 MW, a load factor of 0.7, a plant capacity factor of 0.525 and a plant use factor of 0.85. Find :

(*i*) The daily energy produced.

(*ii*) The reserve capacity of the plant.

(*iii*) The maximum energy that could be produced daily if the plant operating schedule is fully loaded when in operation. [**Ans.** (*i*) 252000 kWh (*ii*) 5000 kW (*iii*) 296470 kWh]

14. Determine the annual cost of a feed water softner from the following data :

Cost = Rs. 80000 ; Salvage value = 5%, Life = 10 years ; Annual repair and maintenance cost = Rs. 2500 ; Annual cost of chemicals = Rs. 5000 ; Labour cost per month = Rs. 300 ; Interest on sinking fund = 5%.

[**Ans.** Rs. 17,140]

15. Estimate the generating cost per kWh delivered from a generating station from the following data :

Plant capacity	= 50 MW
Annual load factor	= 0.4
Capital cost	= Rs. 1.2 crores
Annual cost of wages, taxation etc.	= Rs. 4 lacs
Cost of fuel, lubrication, maintenance etc.	= 1.0 paise per kWh generated.

Interest 5% per annum, depreciation 5% per annum of initial value. [**Ans.** 1.91 paise/kWh delivered]

16. A 100 MW, steam power station is estimated to cost Rs. 20 crores. The operating expenses are estimated as follows :

Cost of fuel and oil	= Rs. 140 lacs per annum
Transportation and storage	= Rs. 20 lacs per annum
Salaries and wages	= Rs. 20 lacs per annum
Miscellaneous	= Rs. 20 lacs per annum

Reckoning interest and depreciation at 10% of the capital cost, calculate the cost of generation per unit, if the average load factor of the power station is 0.6.

What economics could be affected if the load factor was improved to 0.8, the operating expenses increasing by only 10% thereby. [**Ans.** 6 p/kWh, 21% reduction in cost of generation]

17. A steam station has two 110 MW units. Following cost data are given :

Particulars	***Unit A***	***Unit B***
Capital cost	Rs. 2000 per kW	Rs. 2500 per kW
Fixed charge rate	10 per cent	10 per cent
Capacity factor	0.55	0.6
Fuel consumption	1 kg/kWh	0.9 kg/kWh

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Fuel cost	Rs. 80 per 1000 kg	Rs. 80 per 1000 kg
Annual cost of operating, labour, maintenance and supplies	20 per cent of annual cost	15 per cent of annual cost
Utilisation factor	1	1

Calculate the following :

(*i*) Annual plant cost and generation cost of unit A.

(*ii*) Annual plant cost and generation cost of unit B.

(*iii*) Overall generation cost of the station.

[**Ans.** (*i*) Rs. 7,28,78,080 ; 13.75 p/kWh (*ii*) Rs. 75.371648×10^6 ; 13.036 p/kWh (*iii*) 13.378 p/kWh]

18. The annual costs of operating a 15,000 kW thermal power station are as follows :

Cost of plant	= Rs. 900 per kW
Interest, insurance, taxes on plant	= 5 per cent
Depreciation	= 5 per cent
Cost of primary distribution system	= Rs. 500000
Interest, insurance, taxes and depreciation on primary distribution system	= 5 per cent
Cost of secondary distribution system	= Rs. 900000
Interest, taxes, insurance and depreciation on secondary distribution system	= 5 per cent
Maintenance of secondary distribution system	= Rs. 180000

Plant maintenance cost

(*i*) Fixed cost	= Rs. 30000
(*ii*) Variable cost	= Rs. 40000
Operating costs	= Rs. 600000
Cost of coal	= Rs. 60 per tonne
Consumption of coal	= 30000 tonnes
Dividend to stock-holders	= Rs. 1000000
Energy loss in transmission	= 10 per cent
Maximum demand	= 14000 kW
Diversity factor	= 1.5
Load factor	= 0.7

Determine : (*i*) Charge per kW per year (*ii*) Rate per kWh. [**Ans.** (*i*) Rs. 116.6 (*ii*) 3.4 p/kWh]

19. It is proposed to supply a load with a maximum demand of 100 MW and a load factor of 0.4. Choice is to be made from steam, hydro and nuclear power plants. Calculate the overall cost per kWh in case of each machine :

Cost	*Steam power plant*	*Hydro power plant*	*Nuclear power plant*
Capital cost per kW installed	Rs. 1800	Rs. 3600	Rs. 5000
Interest	12%	10%	10%
Depreciation	12%	8%	10%
Operating cost per kWh	15 paise	5 paise	10 paise
Transmission and distribution cost/kWh	0.2 paise	0.8 paise	0.2 paise

[**Ans.** 27.52 p ; 23.57 p ; 38.73 p]

20. A power plant of 150 MW installed capacity has the following data :

Capital cost = Rs. 1800/kW installed ; Interest and depreciation = 12 per cent ;

Annual load factor = 0.6 ; Annual capacity factor = 0.5 ; Annual running charges = Rs. 30×10^6 ; Energy consumed by the power plant auxiliaries = 6 per cent. Calculate :

(*i*) Reserve capacity (*ii*) Generating cost. [**Ans.** (*i*) 25 MW (*ii*) 10.10 paise]

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21. Compare the annual cost of supplying a factory load having a maximum demand of 1 MW at a load factor of 50% by energy obtained from

(*a*) Nuclear power plant (*b*) Public supply

Nuclear power plant :

Capital cost	= Rs. 50000
Cost of fuel	= Rs. 600 per 1000 kg
Fuel consumption	= 30 g per kWh generated
Cost of maintenance etc.	= Re. 0.005 per kWh generated
Wages	= Rs. 20000 per annum
Interest and depreciation	= 10 per cent.

Public supply : Rs. 50 per kW + Re. 0.03 per kWh generated. [**Ans.** Rs. 170740 ; Rs. 181400]

22. A system with a maximum demand of 100000 kW and a load factor of 30% is to be supplied by either (*a*) steam station alone or (*b*) a steam station in conjunction with a water storage scheme, the latter supplying 100 million units with a maximum output of 40000 kW. The capital cost of steam and storage stations are Rs. 600 per kW and Rs. 1200 per kW respectively. The corresponding operating costs are 15 paise and 3 paise per kWh respectively. The interest on capital cost is 15% per annum. Calculate the overall generating cost per kWh and state which of the two projects will be economical.

[**Ans.** 18.425 p/kWh, 15.23 p/kWh]

23. A power station has the installed capacity of 120 MW. Calculate the cost of generation, other data pertaining to power station are given below :

Capital cost	= Rs. 200×10^6
Rate of interest and depreciation	= 18 per cent
Annual cost of fuel oil, salaries and taxation	= Rs. 24×10^6
Load factor	= 0.4

Also calculate the saving in cost per kWh if the annual load factor is raised to 0.5.

[**Ans.** 14.25 paise ; 2.84 paise]

24. A 50 MW generating station has the following data :

Capital cost = Rs. 15×10^6 ; Annual taxation = Rs. 0.4×10^6 ; Annual salaries and wages = Rs. 1.2×10^6 ; Cost of coal = Rs. 65 per tonne ; Calorific value of coal = 5500 kcal/kg ; Rate of interest and depreciation = 12 per cent ; plant heat rate = 33000 kcal/kWh at 100% capacity factor. Calculate the generating cost/kWh at 100% capacity factor. [**Ans.** 39.77 p/kWh]

25. An input output curve of a 10 MW thermal station is given by an equation

$$I = 10^6(18 + 12L + 0.5L^2) \text{ kcal/hour}$$

where I is in kcal/hour and L is the load on power plant in MW.

Find : (*i*) The load at which the efficiency of the plant will be maximum.

(*ii*) The increase in output required to increase the station output from 5 MW to 7 MW by using the input-output equation and by incremental rate curve. [**Ans.** (*i*) 6 MW (*ii*) 36×10^6 kcal/hour]

26. The input-output curve of a 60 MW power station is given by :

$$I = 10^6(8 + 8L + 0.4L^2) \text{ kcal/hour}$$

where I is the input in kcal/hour and L is load in MW.

(*i*) Determine the heat input per day to the power station if it works for 20 hours at full load and remaining period at no load.

(*ii*) Also find the saving per kWh of energy produced if the plant works at full load for all 24 hours generating the same amount of energy. [**Ans.** (*i*) 38592×10^6 kcal/day (*ii*) 4000 kcal/kWh]

27. The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :

$$\frac{dF_1}{dP_1} = 0.06P_1 + 11.4$$

$$\frac{dF_2}{dP_2} = 0.07P_2 + 10$$

where P is in megawatts and F is in rupees per hour.

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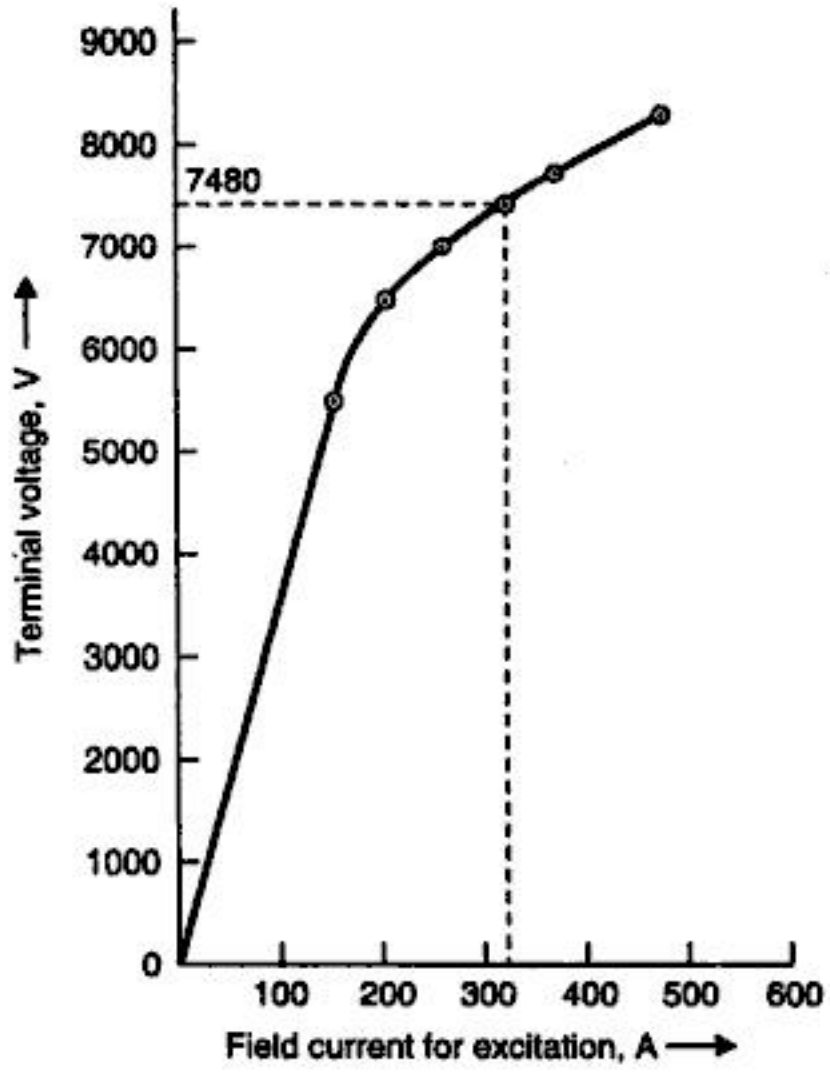

Fig. 10.9

$$\text{Phase voltage} = \frac{6600}{\sqrt{3}} = 3810 \text{ V}$$

$$\text{Now,} \quad E_0 = [(V + I_2R\cos\phi_2 + I_2X\sin\phi_2)^2 + (I_2X\cos\phi_2 - I_2R\sin\phi_2)^2]^{1/2}$$
$$= [(3810 + 67.97 \times 1.05 + 85.97 \times 5)^2 + (67.97 \times 5 - 85.97 \times 1.05)^2]^{1/2}$$
$$= [(4311.2)^2 + (249.6)^2]^{1/2} = 4318.4 \text{ V}$$

E_0 between lines $= 4318.4 \times \sqrt{3} = 7480$ V

From saturation curve (Fig. 10.9) *excitation required to induce an e.m.f. of 7480 V* = **308 A.** **(Ans.)**

☞**Example 10.11.** *Two identical 3-phase alternators work in parallel and supply a total load of 1600 kW at 11000 V at a power factor of 0.92. Each machine supplies half the total power. The synchronous reactance of each is 50 Ω/phase and resistance is 2.5 Ω/phase. The field excitation of the first machine is adjusted so that armature current is 50 A lagging. Determine the armature current of the second alternator, the power factor at which each machine is working and generated voltage of the first alternator.*

Solution. Total load supplied = 1600 kW (at 11000 V and 0.92 p.f.)

Synchronous reactance of each machine/phase = 50 Ω

Resistance/phase = 2.5 Ω

$$\text{Load current at 0.92 p.f.} = \frac{6600 \times 1000}{\sqrt{3} \times 11000 \times 0.92} = 91.3 \text{ A}$$

$$\cos\phi = 0.92, \sin\phi = 0.392$$

$\therefore$ Working component $= 91.3 \times \cos\phi = 91.3 \times 0.92 = 84$ A

Wattless component $= 91.3 \times \sin\phi = 91.3 \times 0.392 = 35.8$ A

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Each alternator supplies half of each component when conditions are identical as shown in current diagram of Fig. 10.10.

Total current supplied per machine = $\frac{91.3}{2}$ = 45.65 A.

Since the steam supply of machine 1 is not changed hence the working components of both machines would remain the same at 42 A. But the *reactive/wattless components will be redivided due to change in excitation.*

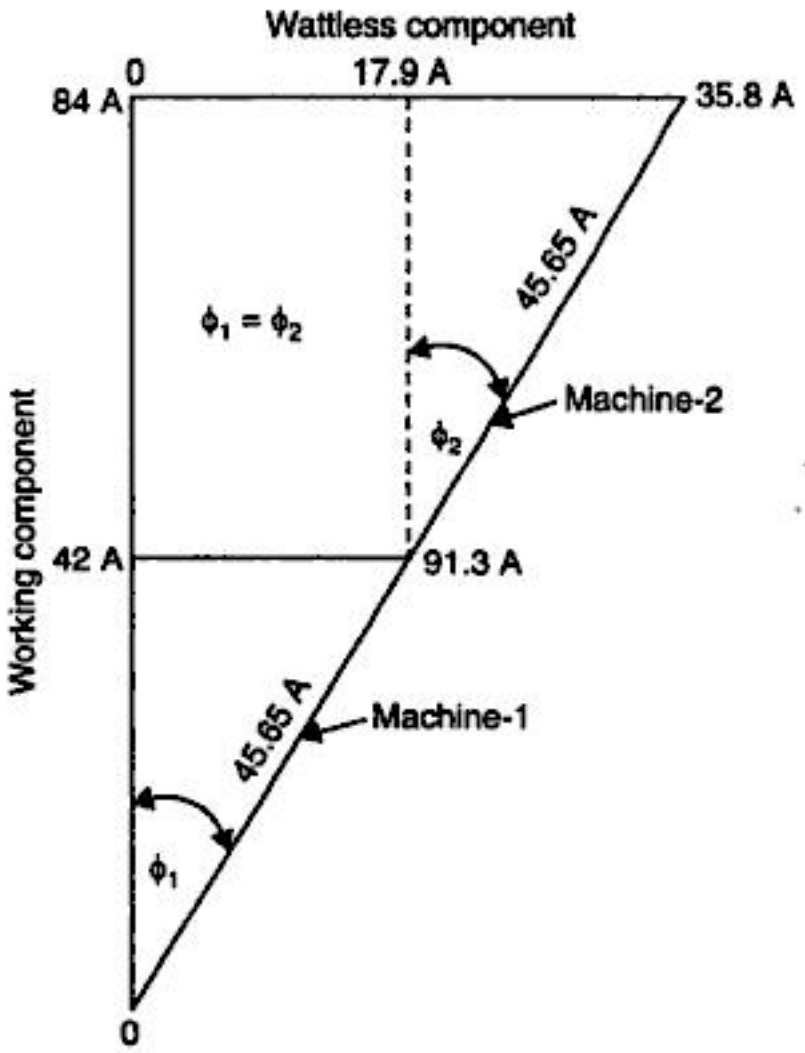

Fig. 10.10

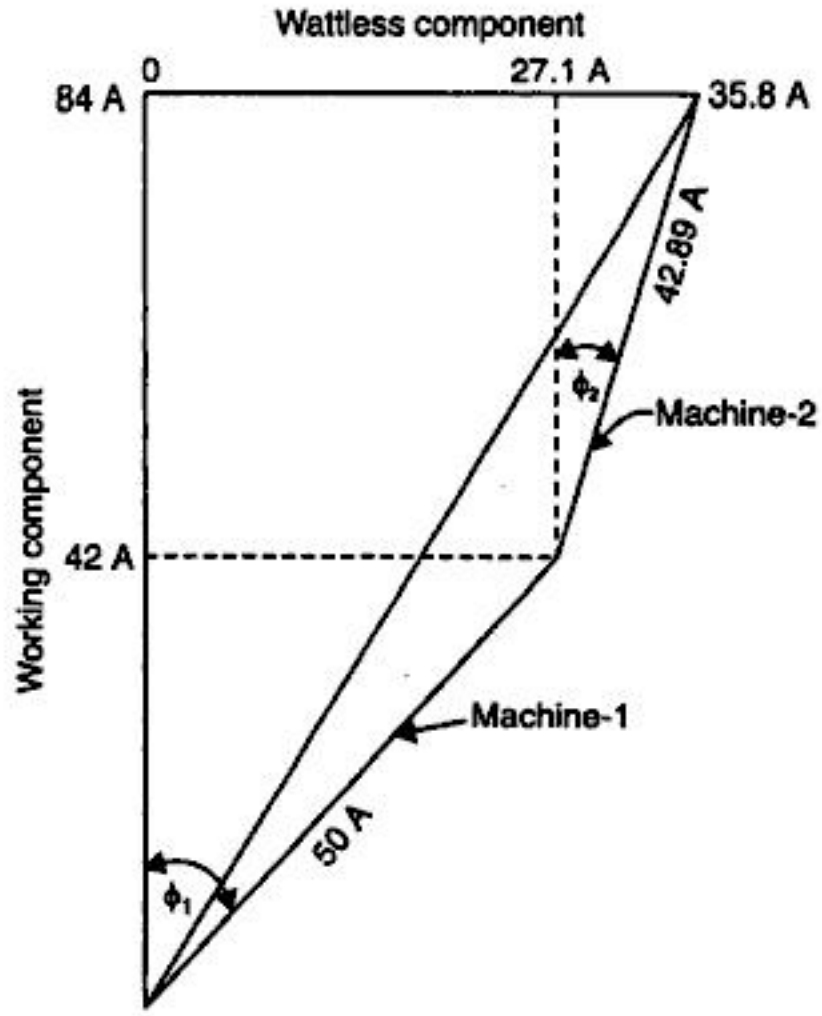

Fig.10.11

The total current taken by machine 1 is changed from 45.65 A to 50 A.

∴ Wattless component for machine 1

$$= \sqrt{50^2 - 42^2} = 27.1 \text{ A}$$

∴ Wattless current delivered by machine 2

$$= 35.8 - 27.1 = 8.7 \text{ A}$$

New current diagram is shown in Fig. 10.11.

(*i*) New total current for machine-2,

$$\mathbf{I_2 = \sqrt{(42)^2 + (8.7)^2} = 42.89 \text{ A.} \quad (Ans.)}$$

(*ii*) $$\mathbf{\cos \phi_1 = \frac{42}{50} = 0.84. \ (Ans.)}$$

$$\mathbf{\cos \phi_2 = \frac{42}{42.89} = 0.979. \quad (Ans.)}$$

(*iii*) Generated voltage of machine-1 :

Terminal voltage/phase $= \frac{11000}{\sqrt{3}} = 6350$ V

$\cos \phi_1 = 0.84$, $\sin \phi_1 = 0.542$

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Refer to Fig. 10.12.

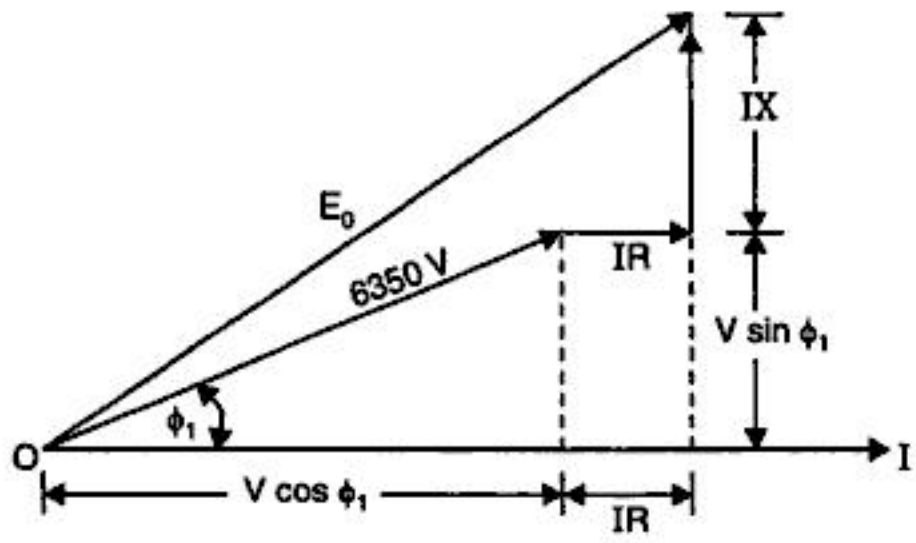

Fig. 10.12

$$E_0 = \sqrt{(V\cos\phi_1 + IR)^2 + (V\sin\phi_1 + IX)^2}$$

$$= \sqrt{(6350 \times 0.84 + 50 \times 2.5)^2 + (6350 \times 0.542 + 50 \times 50)^2}$$

$$= \sqrt{(5459)^2 + (5941.2)^2} = 8068.7 \text{ V}$$

$\therefore$ **Line voltage** $= \sqrt{3} \times 8068.7 =$ **13975.4 V. (Ans.)**

Example 10.12. *A 6600 V, 1200 kVA, 3-phase alternator is delivering full-load at 0.8 p.f. lagging. Its reactance is 25% and resistance negligible. By changing the excitation, the e.m.f. is increased by 30%, at this load. Calculate :*

(i) New current *(ii) Power factor.*

The machine is connected to infinite bus-bars.

Solution. Voltage/phase $= \dfrac{6600}{\sqrt{3}} = 3810$ V

Power factor of load = 0.8 (lag)

Reactance = 25%

(i) New current :

Full-load current $= \dfrac{1200 \times 1000}{\sqrt{3} \times 6600} = 105$ A

Reactance $= \dfrac{3810 \times 25}{105 \times 100} = 9.07\ \Omega$

In Fig. 10.13 current vector OI is taken along X-axis. OV represents bus-bar or terminal voltage and is hence constant.

I_R = Active component of current I

$= 105 \times 0.8 = 84$ A

I_X = Reactive component of current I

$= 105 \times 0.6 = 63$ A

$VL_1 = I_X \,.\, X = 63 \times 9.07 = 571.4$ V

$L_1M_1 = I_R \,.\, X = 84 \times 9.07 = 761.9$ V

$$E_0 = OM_1 = \sqrt{(V + I_X \,.\, X)^2 + (I_R \,.\, X)^2}$$

$$= \sqrt{(3810 + 571.4)^2 + (761.9)^2} = 4447 \text{ V}$$

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If this higher value of excitation were kept constant and the steam supply gradually increased, at what power output would the alternator break from synchronism ? Find also the current and power factor to which this maximum load corresponds. State whether this power factor is lagging or leading.

Solution. Let us assume that the alternator is a three-phase one and that the reactance given is per phase. Hence reactance between the terminals,

$$X = \sqrt{3} \times 10 = 17.32\ \Omega.$$

At unity power factor the reactance drop $IX = 220 \times 17.32 = 3810$ V.

The vector diagram for this condition is shown in Fig. 10.14 (*a*) and the e.m.f. of the alternator is

$$E = \sqrt{V^2 + (IX)^2} = \sqrt{11000^2 + 3810^2} = 11640 \text{ V}.$$

If *the excitation is increased with an unchanged steam supply, i.e. with the same power input, the power output will not change. The result is to give the armature current a lagging reactive component which exerts a demagnetising effect on the main field and neutralizes the increase in excitation.* The vector diagram is Fig. 10.14 (*b*), which shows that the locus of the e.m.f. vector is dotted line perpendicular to $I_R X$. I_R is the power component of the total current = 220 A as before and I_X is the reactive demagnetising component.

With the increased excitation the e.m.f. is

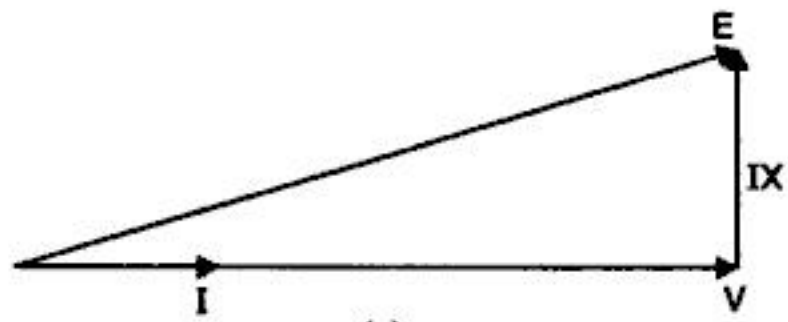
$$E_1 = 1.25\, E = 1.25 \times 11640 = 14550 \text{ V}$$

From Fig. 10.14 (*b*), we have

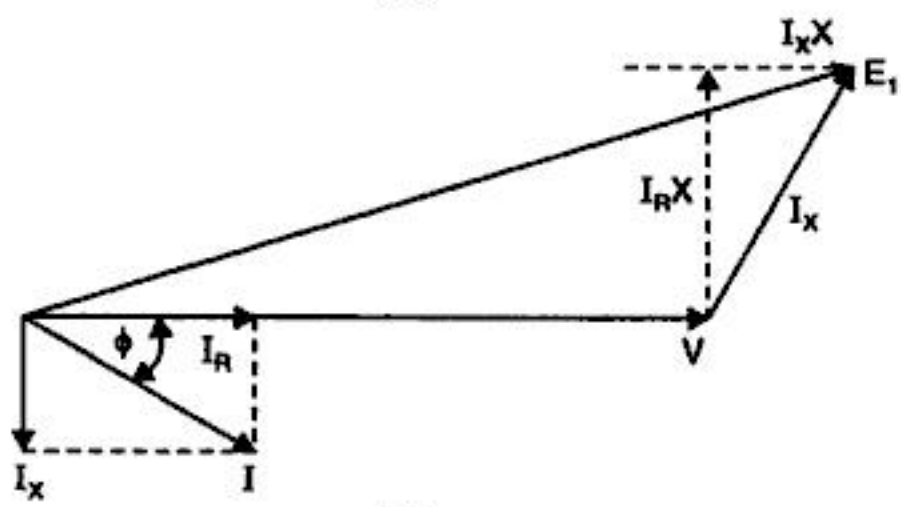
$$V + I_X X = \sqrt{E_1^2 - (I_R X)^2}$$

$$11000 + I_X X = \sqrt{14550^2 - 3810^2} = 14040 \text{ V}$$

$$\therefore \qquad I_X X = 14040 - 11000 = 3040 \text{ V or } I_X = \frac{3040}{17.32} = 175.5 \text{ A}$$



(*a*)



(*b*)

Fig. 10.14

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- In-phase voltage boost helps little in the transfer of real power as it materialises transfer of wattless currents.
- The quadrature voltage boost causes the flow of real power, between stations. This method *increases the inherent stability* and sudden load changes etc. can also be dealt with easily.

10.4.3. Power Limit of Interconnectors

Let us assume that the interconnected stations 1 and 2 are of large capacity (as compared to the loads to be transferred between them) and are coupled by an interconnector which has reactance only. The *maximum power will be transmitted by the interconnector when the voltage V_1 and V_2 displaced by 90°* (see Fig. 10.23). Let the station-2 transmit power to station-1. Under the conditions of maximum power in the interconnector, current I lags the voltage V_2 by 45°, and leads the voltage V_1 by 45°, the former station being at the sending end and the latter being at the receiving end.

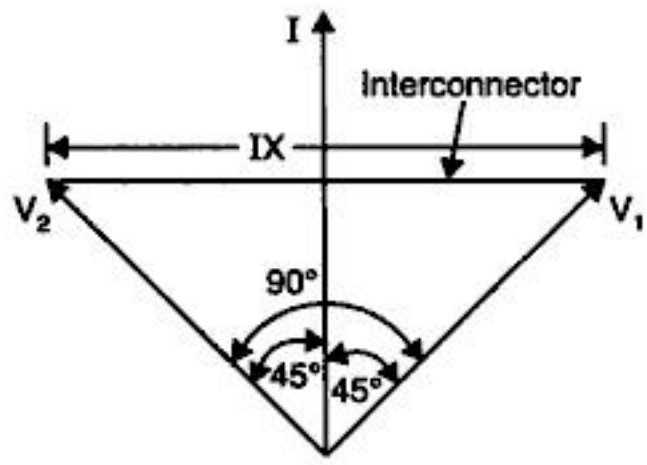

Fig. 10.23. Condition of maximum power transfer.

Synchronous capacity of interconnector

or maximum power transmitted = $VI \cos 45°$

$$= V \times \frac{\sqrt{2}\,V}{X} \times \frac{1}{\sqrt{2}}$$

$$= \frac{V^2}{X} \text{ watts}$$

$$= \frac{V^2}{1000} \text{ kW}$$

$$\left[\because \; I = \frac{V_{12}}{X} = \frac{\sqrt{V^2 + V^2}}{X} = \frac{\sqrt{2}\,V}{X} \right]$$

- **Synchronous capacity** *of an interconnector is defined as the change of kW transmitted per radian change of angular displacement of the two voltages of the two stations.*

Example 10.18. *Two 3-phase generating stations A and B are linked through a 33 kV interconnector having a resistance of 0.84 Ω and a reactance of 4.2 Ω per phase. At station-A the load on the generators is 72 MW at a p.f. of 0.8 lagging and the local load taken by the consumers connected to the A bus-bars is 48 MW at a p.f. of 0.707 lagging.*

Calculate the kW received from station-A by station-B, its p.f. and phase difference between the voltages of A and B.

Solution. *Given :* Interconnector voltage = 33 kV

Interconnector impedance = $0.84 + j4.2$

Load on the generator at station-A = 72 MW at 0.8 p.f. lagging

Load connected to A bus-bars = 48 MW at 0.707 p.f. lagging.

Refer to Fig. 10.24.

Let phase voltage at $A \left(= \frac{33000}{\sqrt{3}} \simeq 19050 \text{ V} \right)$ be taken as reference phasor, so that

$$V_A = 19050\,(1 + j0) \text{ volts}$$

Load current on generators at station-A,

$$I_A = \frac{72 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 0.8} = 1574.6 \text{ A}$$

$$= 1574.6\,(0.8 - j0.6) = (1259.7 - j944.8) \text{ A}$$

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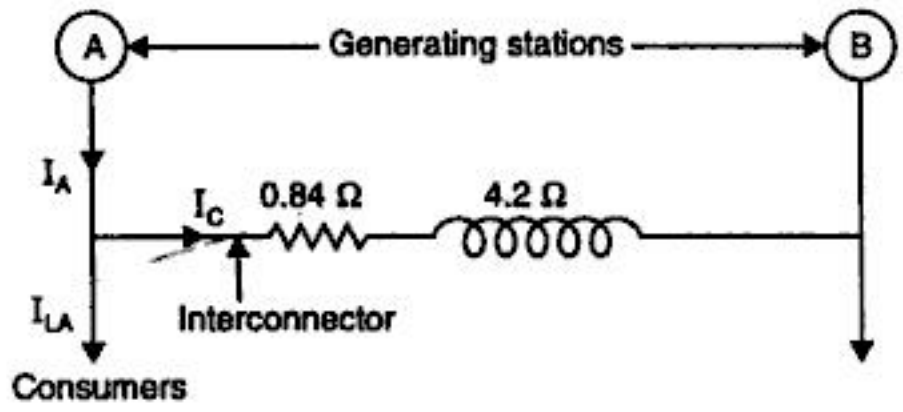

Fig. 10.24

Current due to local load at A,

$$I_{LA} = \frac{48 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 0.707} = 1187.8 \text{ A}$$

$$= 1187.8\,(0.707 - j0.707) = (839.8 - j839.8)$$

Current transferred through the interconnector,

$$I_C = I_A - I_{LA}$$

$$= (1259.7 - j944.8) - (839.8 - j839.8)$$

$$= 419.9 - j105 = 432.8 \angle -14.04°$$

Voltage drop in the interconnector

$$= (419.9 - j105)(0.84 + j4.2)$$

$$= 352.72 + j1763.58 - j88.2 + 441 = (793.72 + j\ 1675.38) \text{ V}$$

Voltage at generating station-B

$$V_B = 19050(1 + j0) - (793.72 + j1675.38)$$

$$= 18256.28 - j1675.38 = 18333 \angle -5.24°$$

Phase difference between V_B and I_C

$$= -14.04° - (-5.24°) = -8.8°$$

i.e. 8.8° with I_C *lagging* V_B

Power factor of the current received by station B

$$= \cos 8.8° = \textbf{0.988 (lagging).} \quad \textbf{(Ans.)}$$

Power received by station B

$$= 3V_B I_C \cos 8.8° = 3 \times 18333 \times 432.8 \times 0.988 \times 10^{-6} \text{ MW}$$

$$= \textbf{23.5 MW.} \quad \textbf{(Ans.)}$$

Phase angle between voltages of station-A and station-B

$$= \textbf{5.24° with } \mathbf{V_A} \textbf{ lagging.} \quad \textbf{(Ans.)}$$

Example 10.19. *Two generating stations A and B are linked by an interconnector cable and reactor having a combined reactance of 4.8 Ω per phase with negligible resistance. Station-A and station-B supply in their own areas loads of 12000 kW at a lagging p.f. of 0.8 and 9600 kW at a p.f. of 0.9 lagging, each at a bus-bar voltage of 11 kV, respectively. The station loads are equalised by the flow of power in the interconnector cable.*

Calculate the power factors of the stations.

Solution. *Given :* Interconnector reactance = 3.36 Ω

Load supplied by station-A in its area = 12000 kW, 0.8 p.f. lagging

Load supplied by station B in its area = 9600 kW, 0.9 p.f. lagging

Bus-bar voltage of each station = 11 kV

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Booster voltages :

Refer to Fig. 10.27. *RE* is any regulating equipment in line *Y* which can provide in-phase and/or quadrature voltage boost required.

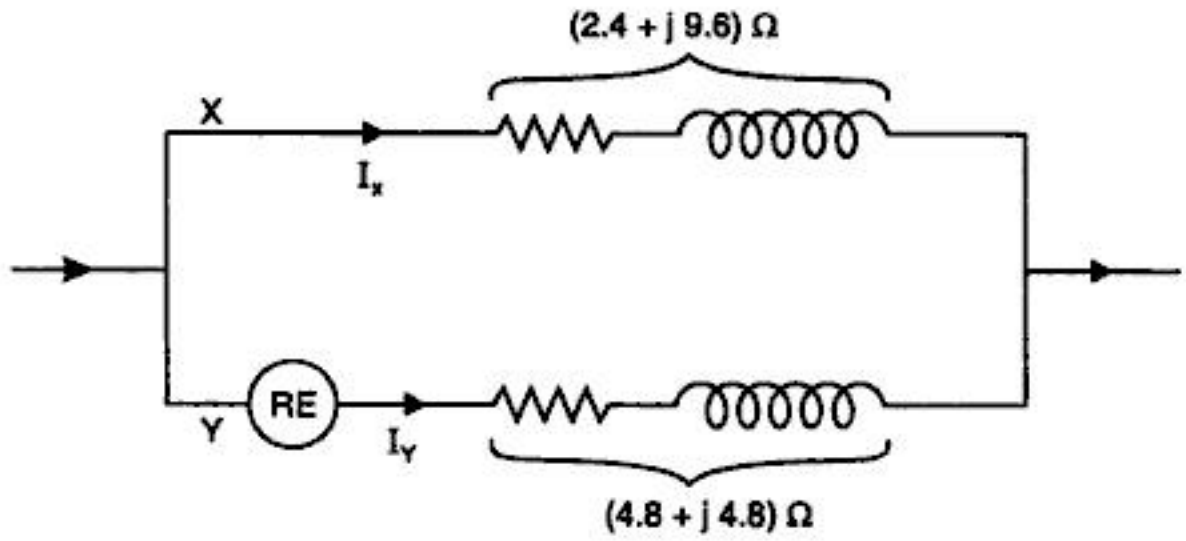

Fig. 10.27

Total load, $P = 10.8$ MW

Power supplied by line $X = \frac{1}{3}P = \frac{1}{3} \times 10.8 = 3.6$ MW

Power supplied by line $Y = \frac{2}{3}P = \frac{2}{3} \times 10.8 = 7.2$ MW

Voltage at receiving end per phase $= \frac{33 \times 10^3}{\sqrt{3}} \simeq 19050$ V (taken as reference vector)

Current flowing through line X $= I_X = \frac{3.6 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 1} = 62.98 \angle 0°$ A

Current flowing through line Y $= I_Y = \frac{7.2 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 1} = 125.96 \angle 0°$ A

Impedance drop in line X $= I_X Z_X = 62.98(2.4 + j9.6) = 151.15 + j604.61$

Impedance drop in line Y $= I_Y Z_Y = 125.96(4.8 + j4.8) = 604.61 + j604.61$

∴ *RE* (Regulating equipment) must provide [assuming that sending end voltage is kept as 19050 + (151.15 + *j*604. 61) = 19201.15 + *j*604.61 V/phase] :

(*i*) *In-phase voltage boost* = 604.61 – 151.15 = **453.46 V/phase. (Ans.)**

(*ii*) *Quadrature voltage boost* = 604.61 – 604.61 = **0 V/phase. (Ans.)**

10.4.4. Voltage, Frequency and Load Control

Voltage Control. The following methods may be used for voltage control :

1. *Injection of reactive power :*

(*i*) Shunt capacitors and reactors.

(*ii*) Series capacitors.

(*iii*) Synchronous compensator.

This is the most fundamental method and is used only when transformers alone will not suffice.

2. *Tap changing transformers*. This is the most widely used method of voltage control.

3. *Booster transformers*. Boosters are oftenly used in distribution feeders when the cost of tap-changing transformers becomes excessive.

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Frequency and Load Control. In an interconnected system where several power stations and generators run in parallel, it is imperative that the system frequency remains constant. In order to maintain frequency constant, both the governor action as well as supplementary controls are required for stable and economic operation. The regulation may be *manual* or *automatic*.

Manual Regulation : In case of a single generator supplying a group of isolated loads, the supply frequency can be easily controlled by adjusting the setting of the turbine governor. But if two or more generators operate in parallel serving a common load, the frequency control becomes more complex/difficult and then the following control methods are employed :

1. *Flat-frequency control.* Refer to Fig. 10.28. Two generators X and Y are operating in parallel and interconnected by a *tie line.* Here only one generator (X) is used for maintaining the frequency constant ; it absorbs all variations in the system loads while the other generator Y supplies constant load. This type of regulation/control is known as flat frequency regulation at station-X.

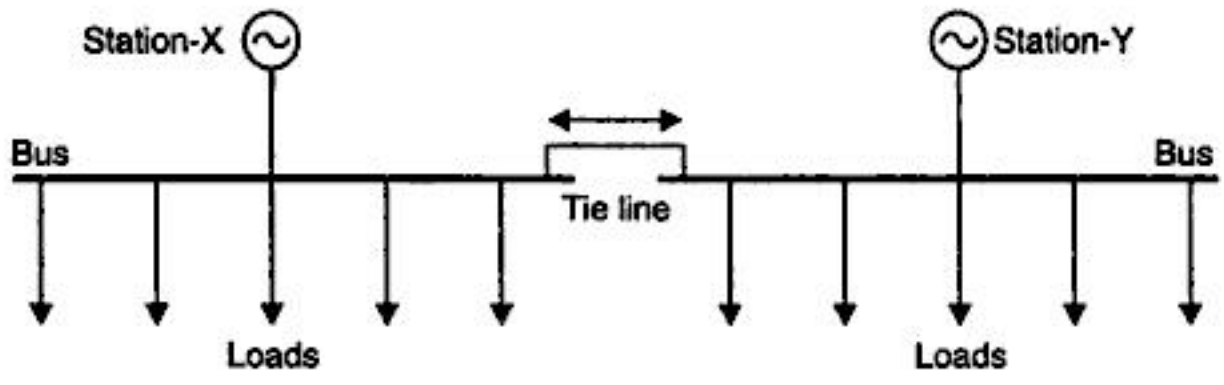

Fig. 10.28. Two generators in parallel.

- The **advantage** of this method is that the *new and more efficient generators can be made to carry the base load and less efficient generator(s) can be used for meeting the load variations.*
- This method has the main **disadvantage** that it *results in random variations in the line powers.*

2. *Parallel-frequency control.* In this method both generators/stations X and Y are regulated to maintain constant frequency when the load at X increases the governor characteristics and generation at both the stations are adjusted (by the operators) so that the system frequency is maintained constant.

3. *Flat tie-line control.* In this method of frequency control, station-X is used to control the frequency while the station-Y meets all load variations in its own area by varying its generation, thus power flow in the tie-line is kept constant irrespective of load demands.

- This method is used when a small system and a large system are interconnected through a tie line ; the large system maintains the system frequency constant while the small system keeps the tie-line power constant. This method is not suitable when two or more large system are connected.

4. *Tie-line bias control.* This is the most widely used method for large inter-connected stations. All power systems contribute towards regulation of frequency and tie-line power flow regardless of where from the frequency variation originates. The control equipment consists of *load frequency controller and tie-line load recorder-controller.*

Automatic regulation. Since in manual regulation a continuous watch on the frequency and loading of various generators is to be kept by the operators, it is not feasible to regulate manually

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6. Two exactly similar turbo-alternators are rated 20 MW each. They are running in parallel. The speed-load characteristics of the driving turbines are such that the frequency of alternator 1 drops uniformly from 50 Hz on no-load to 48 Hz on full-load, and that of alternator 2 from 50 Hz to 48.5 Hz. How will the two machines share a load of 30 MW ? [**Ans.** 12.8572 MW ; 17.1428 MW]

7. Two 750 kW alternators operate in parallel. The speed regulation of one set is 100% to 103% from full-load to no-load and that of the other is 100% to 104%. How will the two alternators share a load of 1000 kW and at what load will one machine cease to supply any portion of the load ?
[**Ans.** 464.3 kW ; 535.7 kW ; 187.5 kW]

8. Two 50 MVA, 3-phase alternators operate in parallel. The settings of the governors are such that the rise in speed from full-load to no-load is 2% in one machine and 3% in the other, the characteristics being straight lines in both cases. If each machine is fully loaded when the total load is 100 MW, what will be the load on each machine when the total load is reduced 60 MW ? [**Ans.** 26 MW, 34 MW]

9. Two 30 MVA, 3-phase alternators operate in parallel. The settings of governors are such that the rise in speed from full-load to no-load is one per cent in one machine and two per cent in the other, the characteristics being straight lines in both cases. If each machine is fully loaded when the total load is 60 MW, what will be no load on each machine when the total load is reduced to 40 MW ?
[**Ans.** 16.7 MW (app.), 23.3 MW (app.)]

10. Two identical 2000 kVA alternators operate in parallel. The governor of first machine is such that the frequency drops uniformly for 50 Hz on no-load to 48 Hz on full-load. The corresponding uniform speed drop of the second machine is 50 to 47.5 Hz.
(*i*) How will the two machines share a load of 3000 kW ?
(*ii*) What is the maximum load at unity p.f. that can be delivered without overloading either machine ?
[**Ans.** 1333 kW assuming u.p.f. ; 1667 kW assuming u.p.f. ; 3600 kW]

Interconnected Stations

11. Two 3-phase generating stations *A* and *B* are linked through a 33 kV interconnector having a resistance of 0.8 Ω and a reactance of 4.0 Ω per phase. At station-*A* the load on the generators is 80 MW at a p.f. of 0.8 lagging and the local load taken by the consumers connected to the *A* bus-bars is 50 MW at a p.f. of 0.707 lagging. Calculate the load in kW received from the station-*A* by station-*B*, its p.f. and phase difference between the voltages of *A* and *B*. [**Ans.** 29.26 MW, 0.977 (lag), 6°14′]

12. Two generating stations *A* and *B* are linked by an interconnector cable and reactor having a combined reactance of 4 Ω per phase with negligible resistance. Station-*A* and station-*B* supply in their own areas loads of 10000 kW at a lagging p.f. of 0.8 and 8000 kW at a p.f. of 0.9 lagging, respectively each at a bus-bar voltage of 11 kV. The station loads are equalised by the flow of power in the interconnector cable. Calculate the power factors of the station *A* and station *B*. [**Ans.** 0.748 (lag) ; 0.9178 (lag)]

13. Two power stations 1 and 2 operate in parallel and are interconnected by a short transmission line. The station capacities are 10 MW and 5 MW respectively and the generating sets have uniform speed regulation (from no-load to full-load) of 2 percent and 4 percent respectively. When the load of each station bus-bar is 6 MW, calculate :
(*i*) Load on the interconnector, and
(*ii*) Output of each station. [**Ans.** (*i*) 3.6 MW ; (*ii*) 9.6 MW , 2.4 MW)]

14. Two 11 kV generating stations 1 and 2 generating 25 MW each at unity p.f. are interconnected by a reactor with a voltage drop of 30 percent for transfer rate of 15 MW. The loads connected to the stations 1 and 2 are 30 MW and 20 MW each at unity p.f. respectively. Calculate the phase angle between the bus-bar voltages of the two generating stations. [**Ans.** 5°44′]

15. From a sub-station, a load of 9 MW is supplied via two 3-ϕ transmission circuits *X* and *Y* having impedances per phase of $(2 + j8)$ ohms and $(4 + j4)$ ohms respectively. In-phase and quadrature boosters are used at the sending end of one line to deliver $\frac{1}{3}$ rd and $\frac{2}{3}$ rd of the total power at unity power factor through circuits *X* and *Y* respectively. Determine the necessary booster voltages.
[**Ans.** 314.94 V/phase (in-phase) ; 0 V/phase (quadrature)]

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The various components are discussed below :

(*i*) *Generating station* (GS). In the generating station electric power is produced by 3-phase alternators operating in parallel. The normal generation voltage is 11 kV (it may be 6.6 kV or even 33 kV in some cases). This voltage is stepped upto 132 kV (or more) with the help of 3-phase transformers. Generally the primary transmission is carried at 66 kV, 132 kV, 220 kV or 400 kV.

Note. *Whereas the use of high voltage leads to several advantages including saving of conductor material and high transmission efficiency, on the other hand, introduces insulation problems and increases cost of switchgear and transformer equipment.*

(*ii*) *Primary transmission.* In this type of transmission, the electric power at 132 kV is supplied to other system by 3-phase, 3-wire overhead system.

(*iii*) *Secondary transmission.* The primary transmission line terminates at the receiving station (RS) where the voltage is reduced to 33 kV by step-down transformers. From this station, the electric power is transmitted at 33 kV to large consumers by 3-phase, 3-wire overhead system, and this forms the secondary transmission.

(*iv*) *Primary distribution.* The secondary transmission line terminates at sub-station (SS) where voltage is reduced from 33 kV to 11 kV. The 11 kV (3-phase, 3-wire) lines run along the important road sides of the city.

Note. The large/big consumers (having demand more than 50 kW) are normally supplied power at 11 kV which they handle it individually with their own sub-stations.

(*v*) *Secondary distribution.* The electric power available at 11 kV from the primary distribution line is delivered to distribution substations (DSS) (located near the localities of the consumers) which step down the voltage to 400 V, 3-phase, 4-wire secondary distribution. The single phase residental lighting load is connected between *any phase and neutral* (230 V) and 3-phase motor load is connected a across 3-phase lines (400 V) directly.

The seconadary distribution system consists of *feeders, distributors* and *service mains* (See Fig. 11.2).

- ***Feeders.*** *These are line conductors which connect the stations to the areas, to be fed by those stations. Normally no tappings are taken from feeders.* They are *designed* mainly from point of view of their *current carrying capacities.*
- ***Distributors.*** *These are the conductors from which several tappings for the supply to the consumers are taken.* They are designed from the point of view of the *voltage drops in them.*
- ***Service mains.*** *These are the conductors which connect the consumers terminals to the distributor.*

11.3. COMPARISON BETWEEN D.C. AND A.C. SYSTEMS OF TRANSMISSION AND DISTRIBUTION

D.C. System :

Advantages. Transmission of electric power by high voltage D.C. systems claim the following *advantages over high voltage A.C. system :*

1. There is greater power per conductor and simple line construction.
2. These systems are economical for long distance bulk power transmission by overhead lines.
3. Ground return is possible.

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4. The voltage regulation problem is much less serious for D.C. since only IR drop is involved, IX drops is nil.
5. There is easy reversibility and controllability of power flow through a D.C. link.
6. No inductance, capacitance, phase displacement and surge problem in D.C. transmission.
7. There is no skin effect in D.C., *X*-section of line conductor is, therefore, fully utilized.
8. A D.C. line has less corona loss and reduced interference with communication circuits.
9. Underground cables can be used because of less potential stress and negligible dielectric loss.
10. No stability problems and synchronizing difficulties.
11. Since the potential stress on the insulation in case of D.C. system is $\frac{1}{\sqrt{2}}$ times that in A.C. system for same working voltage, therefore, less insulation is required in D.C. system.

Disadvantages. The high voltage D.C. systems entail the following *disadvantages* :

1. The systems are costly since installation of complicated converters and D.C. switch gear is expensive.
2. Converters require considerable reactive power.
3. Hormonics are generated which require filters.
4. Converters do not have overload capability.
5. The D.C. voltage cannot be stepped up for transmission of power at high voltages.
6. Electric power cannot be generated at high D.C. voltage due to commutator problems.

A.C. System :

These days electrical energy is almost exclusively generated, transmitted and distributed in the form of A.C.

Advantages :

1. The power can be generated at high voltages.
2. The sub-stations can be maintained easily and at a lesser cost.
3. The A.C. voltage can be stepped-up and stepped-down easily and efficiently with the use of transformers.

Disadvantages :

1. The construction of transmission lines is comparatively difficult.
2. The quantity of copper required is more.
3. In order to provide adequate insulation and to avoid corona loss in case of overhead lines, more spacing between the conductors is required.
4. The alternators need to be synchronized before they are put in parallel.
5. In A.C. system, the resistance of the line is increased due to skin effect.
6. Since an A.C. line has capacitance, therefore, there is a continuous power loss due to charging current even when the line is open.

- *The best method is to employ A.C. system for generation and distribution and D.C. system for transmission.*
- Now-a-days it has become possible to transmit electric power by D.C. system because of introduction of mercury are rectifiers and thyratrons, which can convert A.C. into D.C. and vice-versa directly and at a reasonable cost. Such devices can handle 30 MW at 400 V.

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Fig. 11.3 shows a single line diagram of high voltage D.C. (H.V.D.C.) transmission.

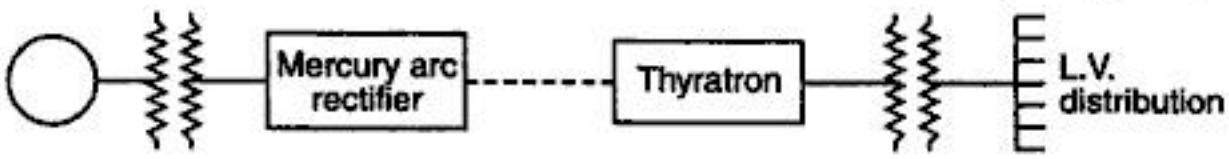

Fig. 11.3. Line diagram of typical H.V.D.C. transmission system.

— Generating station generates electric power which is A.C., stepped to high voltage by the step-up transformers.

— This A.C. power at high voltage is fed to the *mercury arc rectifiers which convert. A.C. into D.C.*

— The transmission of electric power is carried at high D.C. voltage. At the receiving end *D.C. power is converted to A.C. power using thyratrons.* The A.C. supply is then stepped down to low voltage for distribution by step-down transformers.

Classification of Transmission Lines :

For transmission of electrical power three-phase circuits are generally used becuase of economical reasons. Transmission lines may be *classified* as follows :

1. Single line
2. Parallel lines
3. Radial lines
4. Ring system
5. Network.

1. Single line :

- The simplest form is the single line, such as obtained from a power plant supplying its entire output to one load centre over a single-circuit line.
- Such a system has the *disadvantage* that in case of damage to the line the service is *interrupted.*
- Its use is more or less confined to small power systems and is therefore becoming more and more uncommon.

2. Parallel lines :

- Where continuity of service is necessary, it is best to use at least two circuits in parallel, placed either on the same supports or on separate supports.
- *Separate supports afford greater safety* against both lines being damaged at the same time, but the cost is much higher than when two circuits are placed on one support.
- In some cases, where very large quantities of power must be handled, more than two circuits may be run in parallel.

3. Radial lines :

- Invariably a power plant or substation supplies power to the neighbouring territory by means of radial lines.
- These radial lines may be either single circuit for the less important loads or double circuit for the more important loads.

4. Ring system :

- For *systems covering a large territory* the ring system of transmission is very important.
- With this system the main high-voltage power line makes a closed ring, taps being taken off at any advantageous points of the ring, thus supplying a large territory.

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11.5. SYSTEMS OF POWER TRANSMISSION

Although 3-phase, 3-wire A.C. system is universally employed for transmission and 3-phase, 4-wire A.C. system for distribution of electric power, yet under special circumstances other systems can also be used. The *various systems of power transmission are* :

1. **D.C. system :**
   - (*i*) D.C. two-wire.
   - (*ii*) D.C. two-wire with mid-point earthed.
   - (*iii*) D.C. three-wire system.
2. **Single phase A.C. system :**
   - (*i*) Single phase two-wire.
   - (*ii*) Single phase two-wire with mid-point earthed.
   - (*iii*) Single phase three-wire.
3. **Two-phase A.C. system :**
   - (*i*) Two-phase four-wire.
   - (*ii*) Two-phase three-wire.
4. **Three-phase A.C. system :**
   - (*i*) Three-phase 3-wire.
   - (*ii*) Three-phase 4-wire.

It is quite obvious that, out of such a large number of possible systems of transmission it is difficult to decide the best system without making comparison. For various systems of transmission, the basis of comparison is usually the cost of the conductor ; the cost depends upon the volume of the conductor which should be *minimum*. In order to compare the volume of copper required for different systems, the following two cases need to be considered :

(*i*) *Transmission by overhead system :*

In the overhead system of transmission the conductors are insulated from the cross-arms and supporting towers. Since the towers and cross-arms are earthed, therefore, the *maximum voltage between each conductor and earth forms the basis of comparison of volume of conductor.*

(*ii*) *Transmission by underground system :*

In underground system the maximum disruptive stress is between the two conductors (of the cable), so the maximum voltage between conductors forms the basis of comparison.

11.6. COMPARISON OF VOLUME OF CONDUCTOR MATERIAL

The comparison of volume of conductor material will be made in the following *two cases* :

I. Overhead system.

II. Underground system.

For calculating the volume of conductor material required, the following **assumptions** are made for both the above mentioned systems :

1. In all the cases, same power is transmitted (P watts).
2. The distance over which the power is to be transmitted is same (l metres).
3. In each case, the line loss is same (P_{loss} watts).
4. The maximum voltage between any conductor and earth (V_m volts) is same in each case.

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11.6.1. Overhead System

I. D.C. system :

1. ***D.C. two-wire system with one conductor earthed :***

Fig. 11.4 shows a D.C. two-wire system, with one conductor earthed.

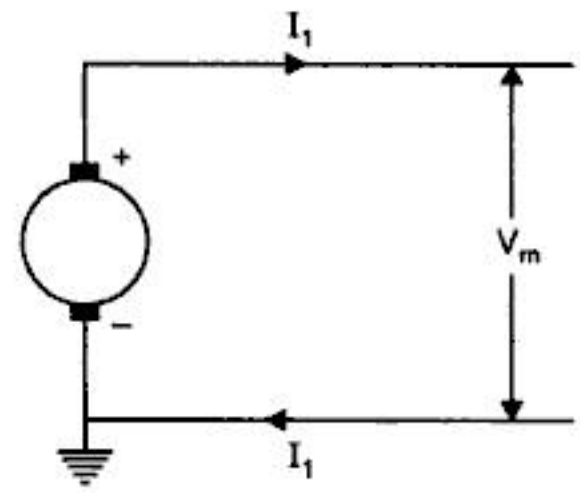

Fig. 11.4

Maximum voltage between conductors = V_m *Volts*

Power to be transmitted = P

Load current, $$I_1 = \frac{P}{V_m}$$

Let R_1 is the resistance of each line conductor.

Then, $R_1 = \dfrac{\rho l}{a_1}$, where a_1 is the X-sectional area of the conductor.

Line losses, $$P_{loss} = 2I_1^2 R_1 = 2\left(\frac{P}{V_m}\right)^2 \frac{\rho l}{a_1} \quad \text{or} \quad a_1 = \frac{2P^2\rho l}{P_{loss} V_m^2}$$

$\therefore$ Volume of conductor material required $= 2\,a_1 l = 2\left(\dfrac{2P^2\rho l}{P_{loss} V_m^2}\right) l = \dfrac{4P^2\rho l^2}{P_{loss}\, V_m^2} = \text{K (say)}$

Usually this system is made as a basis for comparison with other systems.

2. ***D.C. two-wire system with mid-point earthed :*** Refer to Fig. 11.5.

Maximum voltage between the conductors = $2V_m$ volts

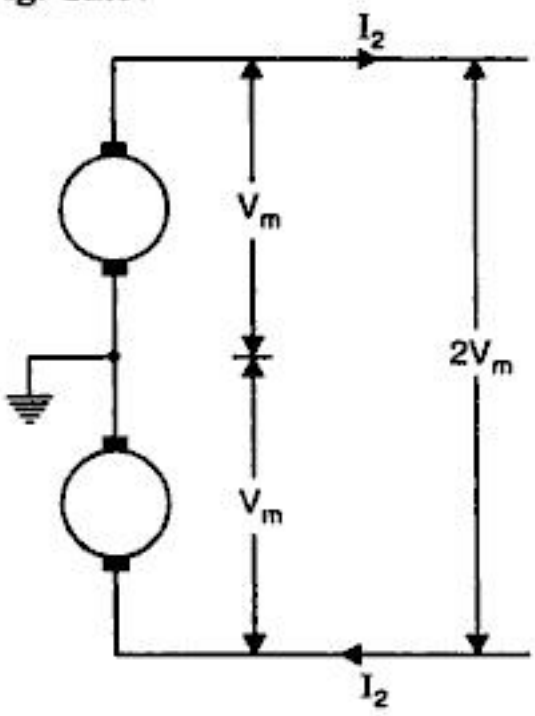

Fig. 11.5

Load current, $$I_2 = \frac{P}{2V_m}$$

Line losses, $P_{loss} = 2I_2^2 R_2$

$$= 2\left(\frac{P}{2V_m}\right)^2 \times \frac{\rho l}{a_2} = \frac{P^2\rho l}{2a_2 V_m^2} \qquad \left(\because\ R_2 = \frac{\rho l}{a_2}\right)$$

or, Area of cross-section, $$a_2 = \frac{P^2\rho l}{2P_{loss} V_m^2}$$

$\therefore$ Volume of conductor material required

$$2a_2 l = 2\left(\frac{P^2\rho l}{2P_{loss} V_m^2}\right) l = \frac{P^2\rho l^2}{P_{loss} V_m^2} = \frac{K}{4} \qquad \left(\because\ K = \frac{4P^2\rho l^2}{P_{loss} V_m^2}\right)$$

Hence, the volume of conductor material required in this system is *one-fourth of that required in two-wire D.C. system with one conductor earthed.*

3. ***D.C. three-wire system :*** Refer to Fig. 11.6.

Maximum voltage between the outer and earth = V_m volts

Load current, $$I_3 = \frac{P/2}{V_m} = \frac{P}{2V_m}$$

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Line losses, $P_{loss} = 2I_3^2R_3 = 2\left(\frac{P}{2V_m}\right)^2 \times \frac{\rho l}{a_3} = \frac{P^2\rho l}{2V_m^2 a_3}$

or, Area of cross-section, $a_3 = \frac{P^2\rho l}{2P_{loss}V_m^2}$

Assuming area of cross-section of neutral wire as half of any outer,

Volume of conductor material required

$$= 2.5\, a_3 l_3 = 2.5\left(\frac{P^2\rho l}{2P_{loss}V_m^2}\right) l$$

$$= \frac{5}{4}\left(\frac{P^2\rho l^2}{P_{loss}V_m^2}\right) = \frac{5}{16}K \qquad \left(\because K = \frac{4P^2\rho l^2}{P_{loss}V_m^2}\right)$$

Hence, the volume of conductor material required in this system is $\frac{5}{16}$*th of that required in two-wire D.C. system with one conductor earthed.*

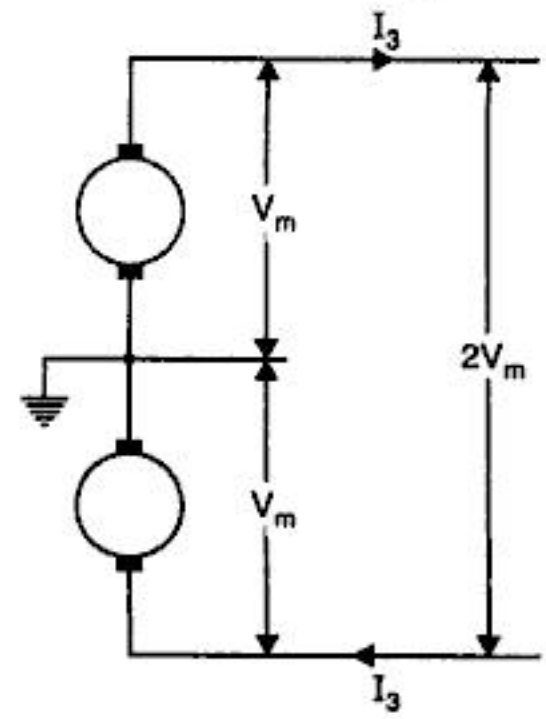

Fig. 11.6

II. A.C. system :

4. ***A.C. single-phase two-wire system with one conductor earthed :*** Refer to Fig. 11.7.

R.M.S. value of voltage between conductor = $\frac{V_m}{\sqrt{2}}$ volts

Load current, $I_4 = \frac{P}{(V_m/\sqrt{2})\cos\phi} = \frac{\sqrt{2}P}{V_m\cos\phi}$

Line losses, $P_{loss} = 2I_4^2R_4 = 2\left(\frac{\sqrt{2}P}{V_m\cos\phi}\right)^2 \times \frac{\rho l}{a_4}$

$$= \frac{4P^2\rho l}{V_m^2\cos\phi \times a_4}$$

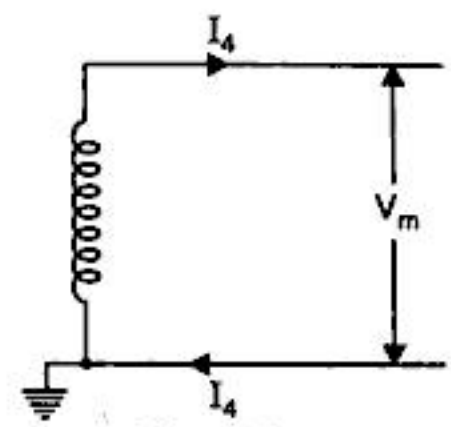

Fig. 11.7

or, Area of cross-section, $a_4 = \frac{4P^2\rho l}{P_{loss}V_m^2\cos^2\phi}$

$\therefore$ Volume of conductor material required = $2a_4 l$

$$= 2 \times \frac{4P^2\rho l}{P_{loss}V_m^2\cos^2\phi} \times l = \frac{2}{\cos^2\phi} \times K$$

Hence, volume of conductor material required in this system is $\frac{2}{\cos^2\phi}$ *times that of two-wire D.C. system with one conductor earthed.*

5. ***A.C. single-phase two-wire system with mid-point earthed :*** Refer to Fig. 11.8.

Maximum voltage between the two wires = $2V_m$

R.M.S. value of voltage between conductors = $\frac{2V_m}{\sqrt{2}} = \sqrt{2}\,V_m$ volts

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Load current, $I_5 = \dfrac{P}{(\sqrt{2}V_m)\cos\phi}$

Line losses, $P_{loss} = 2I_5^2R_5 = 2\left[\dfrac{P}{(\sqrt{2}V_m)\cos\phi}\right]^2 \times \dfrac{\rho l}{a_5}$

$$= \frac{P^2\rho l}{V_m^2\cos^2\phi \times a_5}$$

or, Area of cross-section, $a_5 = \dfrac{P^2\rho l}{P_{loss}V_m^2\cos^2\phi}$

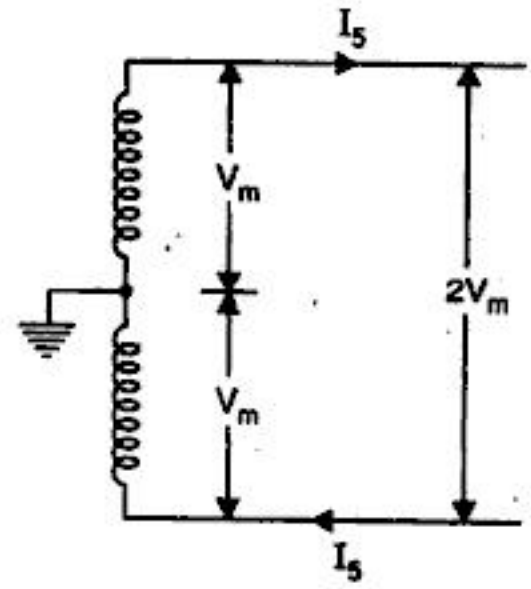

Fig. 11.8

∴ Volume of conductor material required

$$= 2a_5l = 2\left(\frac{P^2\rho l}{P_{loss}V_m^2\cos\phi}\right)\times l = \frac{2}{\cos^2\phi}\times\frac{P^2\rho l^2}{P_{loss}V_m^2}$$

$$= \frac{K}{2\cos^2\phi} \qquad \left(\because K = \frac{4P^2\rho l^2}{P_{loss}V_m^2}\right)$$

Hence, volume of conductor material required in this system is $\dfrac{1}{2\cos^2\phi}$ *times that of two-wire D.C. system with one conductor earthed.*

6. ***A.C. single-phase three-wire system :*** Refer to Fig. 11.9.

R.M.S. value of voltage between outer and earth = $\dfrac{V_m}{\sqrt{2}}$ volts

Load current, $I_6 = \dfrac{P/2}{(V_m/\sqrt{2})\cos\phi} = \dfrac{P}{\sqrt{2}V_m\cos\phi}$, assuming balanced load.

Line losses, $P_{loss} = 2I_6^2R_6 = 2\times\left(\dfrac{P}{\sqrt{2}V_m\cos\phi}\right)^2 \times \dfrac{\rho l}{a_6}$

$$= \frac{P^2\rho l}{V_m^2\cos^2\phi\times a_6}$$

or, Area of cross-section, $a_6 = \dfrac{P^2\rho l}{P_{loss}V_m^2\cos^2\phi}$

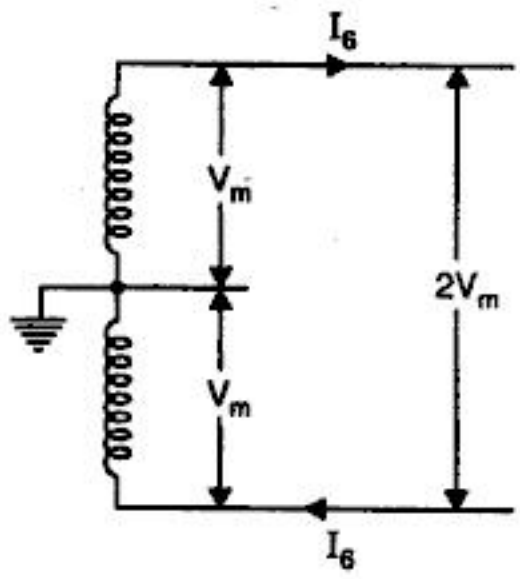

Fig. 11.9

Assuming the area of cross-section of neutral wire to be half that of any of the outers,
Volume of conductor material required

$$= 2.5\,a_6l = 2.5\left(\frac{P^2\rho l}{P_{loss}V_m^2\cos^2\phi}\right)\times l = \frac{2.5P^2\rho l^2}{P_{loss}V_m^2\cos^2\phi}$$

$$= \frac{2.5}{\cos^2\phi}\times\frac{P^2\rho l^2}{P_{loss}V_m^2} = \frac{5}{8\cos^2\phi}\times K \qquad \left(\because K = \frac{4P^2\rho l^2}{P_{loss}V_m^2}\right)$$

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Hence volume of conductor material required in this system is $\frac{5}{8\cos^2\phi}$ *times that required in two-wire D.C. system with one conductor earthed.*

7. ***A.C. two-phase four-wire system :*** Refer to Fig. 11.10.

R.M.S. value between the outers $= \frac{2V_m}{\sqrt{2}} = \sqrt{2}V_m$

Load supplied by each phase $= \frac{P}{2}$

Load current per phase, $I_7 = \frac{P}{2\sqrt{2}V_m \cos\phi}$

Line losses, $P_{loss} = 4I_7^2 R_7$

$$= 4 \times \left(\frac{P}{2\sqrt{2}V_m \cos\phi}\right)^2 \times \frac{\rho l}{a_7}$$

$$= \frac{P^2 \rho l}{2V_m^2 \cos^2\phi \times a_7}$$

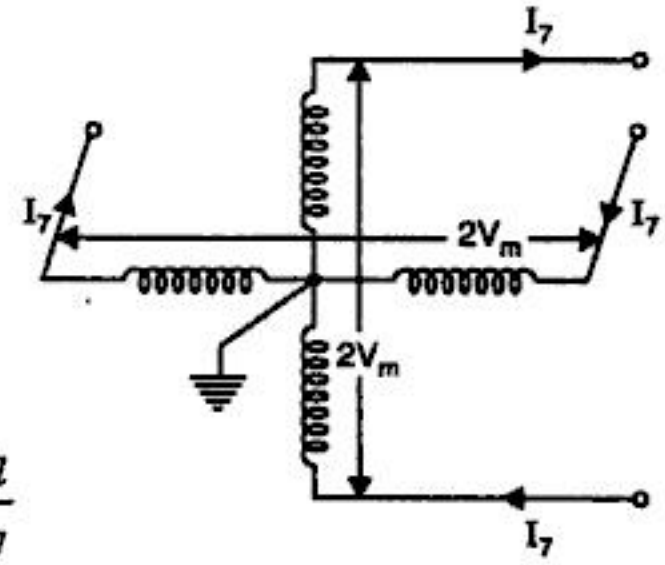

Fig. 11.10

$\therefore$ Area of cross-section, $a_7 = \frac{P^2 \rho l}{2P_{loss}V_m^2 \cos^2\phi}$

$\therefore$ Volume of conductor material required

$$= 4a_7 l = 4 \times \frac{P^2 \rho l}{2P_{loss}V_m^2 \cos^2\phi} \times l$$

$$= \frac{1}{2\cos^2\phi} \times \frac{4P^2 \rho l^2}{P_{loss}V_m^2} = \frac{1}{2\cos^2\phi} \times K$$

Hence, the volume of conductor material required for this system is $\frac{1}{2\cos^2\phi}$ *times that required in two-wire D.C. system with one conductor earthed.*

8. ***A.C. two-phase three-wire system :*** Refer to Fig. 11.11.

R.M.S. value of voltage between outer and neutral, considering balance load, $= \frac{V_m}{\sqrt{2}}$ volts

Current in each of the outer conductors,

$$I_8 = \frac{P/2}{(V_m/\sqrt{2})\cos\phi} = \frac{P}{\sqrt{2}V_m \cos\phi}$$

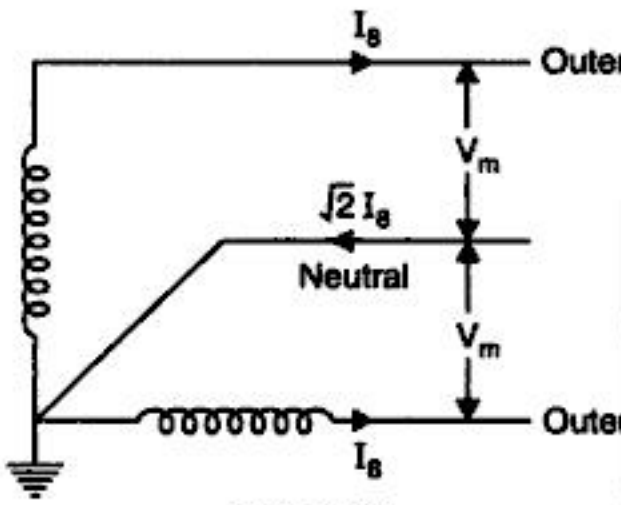

Fig. 11.11

Current in the neutral wire

= phasor sum of currents in outer wires

$= \sqrt{I_8^2 + I_8^2} = \sqrt{2}I_8$ (currents in the outers being 90° apart)

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R.M.S. value of voltage between outers = $\frac{V_m}{\sqrt{2}}$ volt

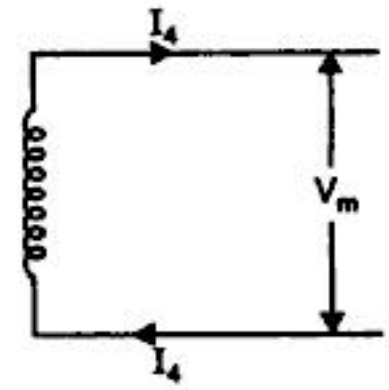

Fig. 11.17

Load current, $I_4 = \frac{P}{V_m / \sqrt{2} \cos\phi} = \frac{\sqrt{2}P}{V_m \cos\phi}$

Line losses, $P_{loss} = 2I_4^2 R_4 = 2\left(\frac{\sqrt{2}P}{V_m \cos\phi}\right)^2 \times \frac{\rho l}{a_4}$

$$= \frac{4P^2\rho l}{V_m^2 \cos^2\phi \times a_4}$$

or, Area of cross-section, $a_4 = \frac{4P^2\rho l}{P_{loss} V_m^2 \cos^2\phi}$

∴ Volume of conductor material required

$$= 2a_4 l = 2\left(\frac{4P^2\rho l}{P_{loss} V_m \cos^2\phi}\right) \times l = \frac{2}{\cos^2\phi} \times \frac{4P^2\rho l^2}{P_{loss} V_m} = \frac{2}{\cos^2\phi} \times K$$

Hence, volume of conductor material required is $\frac{2}{\cos^2\phi}$ *times that required for two-wire D.C. system.*

5. ***A.C. single-phase, two-wire system with mid-point earthed :*** Refer to Fig. 11.18

Maximum value of voltage between outers = V_m volts

R.M.S. value of voltage between outers = $\frac{V_m}{\sqrt{2}}$ volts

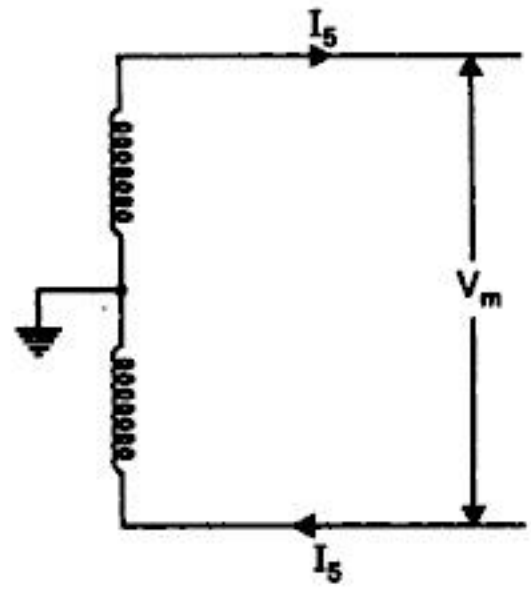

Fig. 11.18

Load current, $I_5 = \frac{P}{(V_m / \sqrt{2})\cos\phi} = \frac{\sqrt{2}P}{V_m \cos\phi}$

Line losses, $P_{loss} = 2I_5^2 R_5 = \left(\frac{\sqrt{2}P}{V_m \cos\phi}\right)^2 \times \frac{\rho l}{a_5}$

$$= \frac{4P^2\rho l}{V_m^2 \cos^2\phi \times a_5}$$

or, Area of cross-section, $a_5 = \frac{4P^2\rho l}{P_{loss} V_m^2 \cos^2\phi}$

∴ Volume of conductor material required

$$= 2a_5 l = 2 \times \left(\frac{4P^2\rho l}{P_{loss} V_m^2 \cos^2\phi}\right) \times l = \frac{2}{\cos^2\phi}\left(\frac{4P^2\rho l^2}{P_{loss} V_m^2}\right) = \frac{2}{\cos^2\phi} \times K$$

Hence, volume of conductor material required in this system is $\frac{2}{\cos^2\phi}$ *times that required in two-wire D.C. system.*

6. ***A.C. single phase, three-wire system.*** Refer to Fig. 11.19.

Assuming load to be balanced, the system reduces to a single-phase, two-wire A.C. system except that a neutral wire is provided additionally. Assuing the cross-sectional area of the neutral wire to be half of either of the outers,

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10. ***D.C. three-phase, four-wire system.*** Refer to Fig. 11.23.

Assuming balanced load, this system reduces to three-phase three-wire A.C. system except that an additional wire known an neutral wire is provided. Further assuming the cross-sectional area of the neutral wire to be half that of the line conductor,

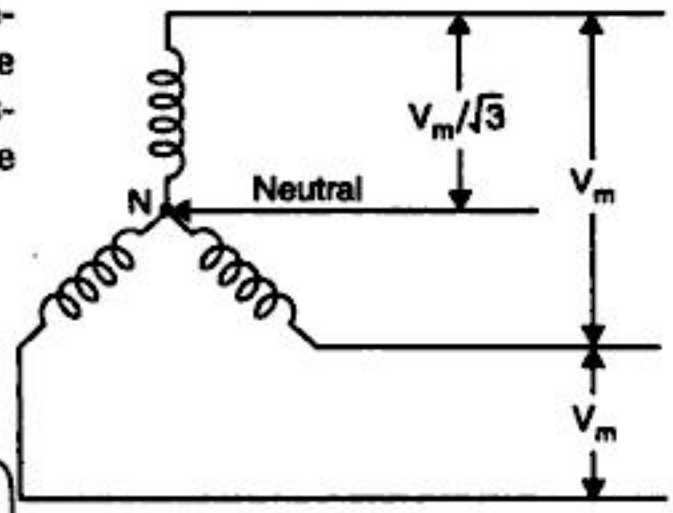

Fig. 11.23

Volume of conductor material required = $3.5\, a_3 l$

$$= 3.5\left(\frac{2P^2\rho l}{P_{loss}V_m^2\cos^2\phi}\right)\times l$$

$$= \frac{7}{\cos^2\phi}\times\frac{P^2\rho l^2}{P_{loss}V_m^2} = \frac{1.75}{\cos^2\phi}\times K \qquad \left(\because\ K = \frac{4P^2\rho l^2}{P_{loss}V_m^2}\right)$$

Hence, volume of conductor material required in this system is $\frac{1.75}{\cos^2\phi}$ *times that required in two-wire D.C. system.*

Summary of Results of Comparison of Various Systems of Transmission

The summary of results of comparison of various systems of transmission is given below :

System	*Volume of conductor material required*	
	Maximum voltage between conductor and earth	*Maximum voltage between any two conductors*
1. ***D.C. system***		
(*i*) Two-wire	1	1
(*ii*) Two-wire with mid-point earthed	0.25	1
(*iii*) Three-wire	0.3125	1.25
2. ***A.C. single-phase system***		
(*i*) Two-wire	$\frac{2}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
(*ii*) Two-wire with mid-point earthed	$\frac{0.5}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
(*iii*) Three-wire	$\frac{0.625}{\cos^2\phi}$	$\frac{2.5}{\cos^2\phi}$
3. ***A.C. two-phase system***		
(*i*) Two-phase four-wire	$\frac{0.5}{\cos^2\phi}$	$\frac{2}{\cos^2\phi}$
(*ii*) Two-phase three-wire	$\frac{1.457}{\cos^2\phi}$	$\frac{2.914}{\cos^2\phi}$
4. ***A.C. three-phase system***		
(*i*) Three-phase three-wire	$\frac{0.5}{\cos^2\phi}$	$\frac{1.5}{\cos^2\phi}$
(*ii*) Three-phase four-wire	$\frac{0.583}{\cos^2\phi}$	$\frac{1.75}{\cos^2\phi}$

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From this comparison the following points *emerge* :

1. From economic point of view (saving in conductor material) *D.C. system is ideal for transmission, particularly when p.f. of the load which is usually less than unity is taken into consideration.*
2. Among A.C. systems, *3-phase, 3-wire system is most suitable* because of the following reasons :
   (*i*) There is considerable saving in conductor material.
   (*ii*) It is convenient and efficient.

Example 11.1. *A 3-wire D.C. system is converted to a 3-phase, 4-wire, A.C. system by the addition of another wire equal in section to one of the outers. Find the percentage additional load that can be supplied for the same effective voltage between outers and neutral at the consumer's terminals and the percentage loss.*

Assume that load is balanced and in the A.C. system the p.f. is 0.95.

Solution. Let, V = Voltage between outer and neutral in both the cases,
I_1 = Current in 3-wire D.C. system, and
I_2 = Current in 4-wire A.C. system.

3-wire D.C. system :

Power suplied, $P_1 = 2VI_1$

Power loss, $P_{loss} = 2 I_1^2 R$ ...(R = resistance of each conductor)

%age power loss $= \dfrac{2I_1^2R}{2VI_1} \times 100 = \dfrac{100I_1R}{V}$ ...(*i*)

3-phase, 4-wire A.C. system :

Power supplied, $P_2 = 3VI_2 \cos \phi = 3VI_2 \times 0.95 = 2.85VI_2$

Power loss, $P_{loss} = 3I_2^2R$

%age power loss $= \dfrac{3I_2^2R}{2.85VI_2} \times 100 = \dfrac{100I_2R}{0.95V}$ ...(*ii*)

(Since load is balance, therefore the current in the neutral will be zero)

As percentage loss is same (*given*), therefore,

$$\frac{100I_1R}{V} = \frac{100I_2R}{0.95V} \quad \text{or} \quad I_2 = 0.95\, I_1$$

$\therefore$ Power supplied in 3-phase, 4-wire system,

$$P_2 = 2.85\, V \times (0.95\, I_1) \simeq 2.71\, VI_1$$

Hence, percentage increase in load supplied

$$= \frac{P_2 - P_1}{P_1} \times 100 = \frac{2.71VI_1 - 2VI_1}{2VI_1} \times 100 = \mathbf{35.5\%.} \quad \textbf{(Ans.)}$$

Example 11.2. *A three-phase, four-wire A.C. system is employed for lighting. Compare the amount of copper required with that needed for a two-wire D.C. system with the same lamp voltage.*

Assume balanced load, same losses and neutral having half the cross-section of the respective outers. **(M.U.)**

Solution. ***2-wire D.C. system :***

Load current, $I_1 = \dfrac{P}{V}$ amp.

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In other words, the ***variable part of anual charge should be equal to the cost of annual losses due to energy wasted in the conductor for most economical working.***

The above statement is **Kelvin's law.** Although this law hold true theorectically, but in actual working its application involves complicacies/difficulties.

Fig. 11.28 shows the *graphical representation of Kelvin's law.* The lowest point A on the sum curve ($P_1 + P_2a + P_3/a$) which coresponds to the point of intersection of (P_2a) and $\frac{P_3}{a}$ curves gives the most economical conductor size.

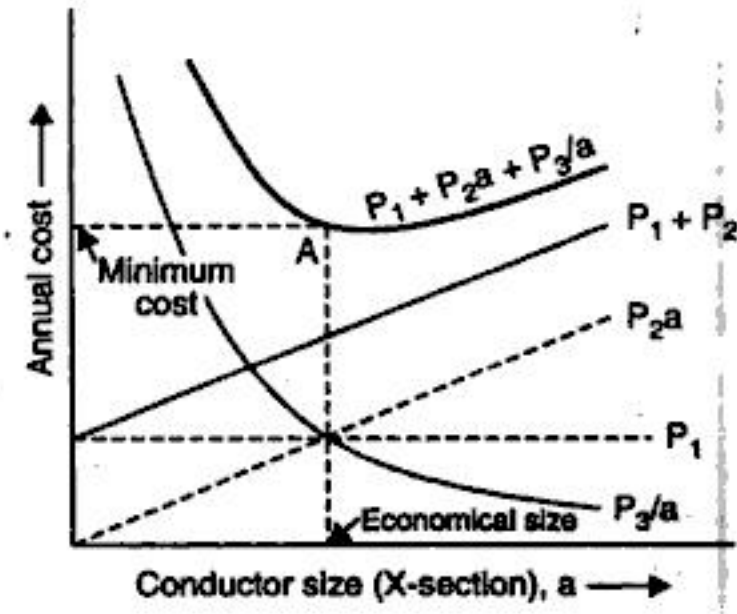

Fig. 11.28

Limitations of Kelvin's law :

Following are the *limitations* of Kelvin's law :

1. It is difficult to estimate the loss of energy in line without actual load curves, which are not available at the time of estimation.
2. The assumption that annual charge is of form ($P_1 + P_2a$) is strictly speaking not true. For example, in underground cables neither the cost of laying the cables nor the cost of cable dielectric and sheath vary in this manner.
3. The Kelvin's law does not take into account factor like mechanical strength, safe current density, corona loss etc
4. The conductor size determined may be of such a small X-section that it may cause too much voltage drops in the line.
5. Interest and depreciation on the capital outlay cannot be accurately determined.

Example 11.8. *A two-conductor cable one km long, is required to supply a constant load of 180 A throughout the year. The cost of cable is Rs. (120 a + 60) per metre , where 'a' is the area of X-section of the conductor in cm². The cost of enegy is 20 P per kWh and interest and depreciation charges amount to 10 per cent. Specific resistivity of copper is 1.84 μΩ cm. Find the most economical X-section of the cable.*

Solution. *Given :* $l = 1$ km ; $I = 180$ A ; cost of cable per metre length = Rs $(120a + 60)$; cost of energy = 20 *p*/kWh ; Interest and depreciation charges = 10% ; $\rho = 1.84$ μΩ cm.

Most economical X-section of the cable, a (cm²) :

Resistance of each conductor, R

$$R = \frac{\rho l}{a} = \frac{1.84 \times 10^{-6} \times (1000 \times 100)}{a} = \frac{0.184}{a}\ \Omega$$

$$\text{Energy cost per annum} = \frac{2I^2R \times 8760}{1000}$$

$$= \frac{2 \times (180)^2 \times 0.184 \times 8760}{a \times 1000} = \frac{104447}{a}\ \text{kWh}$$

$$\text{Annual cost due to energy lost} = \text{Rs. } \frac{20}{100} \times \frac{104447}{a} = \text{Rs. } \frac{20889.4}{a}$$

Capital cost (variable) of the cable = Rs. $120a \times 1000 = 120000\ a$

Annual charges on account of interest and depreciation on variable cost of cable

$$= \text{Rs. } \frac{10}{100} \times 120000a = 12000\ a$$

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$$\text{Energy lost per annum} = \frac{3I^2R \times 8760}{1000} \times \text{loss load factor}$$

$$= \frac{3 \times (61.7)^2 \times (1.72 \times 10^{-6} \times l \times 1000 \times 100) \times 8760}{a \times 1000} \times 0.386$$

$$= \frac{6642.2\,l}{a}$$

$$\text{Annual cost due to energy lost} = \text{Rs.}\ \frac{5}{100} \times \frac{6642.2\,l}{a} = \text{Rs.}\ \frac{332.11\,l}{a}$$

For most economical section of the conductor,

Variable annual charge = Annual cost of energy lost

i.e.,
$$8000\,al = \frac{332.11\,l}{a}$$

$$a = \sqrt{\frac{332.11}{8000}} = \mathbf{0.204\ cm^2.}\quad \textbf{(Ans.)}$$

Example 11.13. *Assume the following daily load cycle for a 11 kV, 3-phase line :*

(i) 2.4 MW at unity p.f. for 6 hours,

(ii) 0.8 MW at 0.8 p.f. (lag) for 6 hours, and

(iii) 0.4 MW at unity p.f. for 12 hours.

If the resistance of the line conductor of 1 cm² X-sectional area is 0.19 ohm and energy cost is Re 1. per unit, calculate the annual energy lost. **(M.U.)**

Solution. Currents corresponding to loads of different values for given load cycle are :

$$I_1 = \frac{2.4 \times 10^6}{\sqrt{3} \times 11 \times 10^3 \times 1} = 126\ \text{A}$$

$$I_2 = \frac{0.8 \times 10^6}{\sqrt{3} \times 11 \times 10^3 \times 0.8} = 52.5\ \text{A}$$

$$I_3 = \frac{0.4 \times 10^6}{\sqrt{3} \times 11 \times 10^3 \times 1} = 21\ \text{A}$$

∴ Energy loss during the period of 24 hours in each line

$$= (126)^2 \times 0.19 \times 6 + (52.5)^2 \times 0.19 \times 6 + (21)^2 \times 0.19 \times 12$$

$$= 18099 + 3142 + 1005 = 22246\ \text{Wh} = 22.246\ \text{kWh per day}$$

∴ Total energy loss annually in all the three conductors

$$= 3 \times 22.246 \times 365 = 24359\ \text{kWh/year}$$

∴ *Annual energy cost* = Rs. 24359 × 1 = **Rs. 24359.** **(Ans.)**

Example 11.14. *Determine the most economical size of a 3-phase line which supplies the following loads at 10 kV :*

(i) 1,000 kW at 0.8 p.f. (lag) for 10 hours,

(ii) 500 kW at 0.9 p.f. (lag) for 8 hours, and

(iii) 100 kW at u. p. f. for 6 hours.

The above gives the daily load cycle. The cost per km of the completely erected line is Rs. (8000 a + 1500) where a is the area of X-section of each conductor in cm². The combined interest and depreciation is 10 percent per annum of capital cost. Cost of energy losses is 5 paise per kWh. Resistivity of conductor material = 1.72 × 10⁻⁶ Ω-cm. **(AMIE, Power Systems)**

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12

Mechanical Design of Overhead Lines

12.1. Introduction. 12.2. Main component of overhead lines. 12.3. Conductors. 12.4. Line supports. 12.5. Overhead line insulators—Introduction—Insulating materials—Types of insulators—Causes of failure of insulators—Testing of insulators—Potential distribution over a string of suspension insulators. 12.6. Sag in overhead lines. 12.7. Stringing chart. 12.8. Vibration and vibration dampers. 12.9. Corona—General aspects—Theory of corona formation—Factors affecting corona—Advantages and disadvantages of corona—Corona loss and its control—Important terms relating to corona. Highlights—Theoretical Questions—Unsolved Examples.

12.1. INTRODUCTION

The transmission or distribution of electric power can be carried out by means of overhead lines or underground cables. The underground cables are rarely employed for power transmission because of the two *reasons* : (*i*) Power is generally transmitted over long distances to load centres ; (*ii*) The installation costs are very high. The use of underground system is limited to congested areas where safety and good appearance are the main consideration. Thus, as a rule, transmission of power over long distances is carried out by using overhead lines.

In this chapter we shall discuss topics relating to mechanical design of overhead lines *viz.*, line supports, conductor materials, overhead line insulators, sag etc.

12.2. MAIN COMPONENT OF OVERHEAD LINES

The main components of an overhead line are :

1. *Conductors.* They carry power from sending end station to receiving end station.

2. *Supports.* These may be poles or towers (depending upon the working voltage and the region where these are used) and keep the conductors at a suitable level above the ground.

3. *Cross-arms.* They provide support to the insulators.

4. *Insulators*. They provide insulation to high voltage wire with the metal structure and also provide support to the conductor. They also provide support to bus-bar conductors and other live high voltage equipment terminals.

5. *Miscellaneous items :*

(*i*) Phase plates
(*ii*) Lightning arrestors
(*iii*) Vee guards
(*iv*) Guard wires
(*v*) Anticlimbing wires
(*vi*) Fuse and isolating switches etc.

12.3. CONDUCTORS

The material of the conductor to be used for transmission and distribution of electric power should possess the following *characteristics* :

(*i*) High electrical conductivity (*i.e.*, low resistivity).

(*ii*) High tensile strength (to withstand mechanical stress).

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Table 12.3. Formulae for Stranded Conductor

1. *No. of wires in the centre*	1 wire	3 wires	4 wires
2. *No. of wires in the nth layer from the centre*	$6n$	$3 + 6n$	$4 + 6n$
3. *Total no. of wires in a stranded conductor having n layers*	$1 + 3n(1 + n)$	$3(1 + n)^2$	$(4 + 3n)(1 + n)$
4. *Diameter over the nth layer in cm, where, d = dia. of each wire in cm.*	$(1 + 2n)\,d$	$(2.155 + 2n)d$	$(2.414 + 2n)\,d$

The stranded conductors are expressed as follows : 7/2.24, 19/2.50, 37/2.06, and so on.

First number (*i.e.*, 7, 19, 37, etc.) indicates ..... Total no. of wires.

Second number (*i.e.*, 2.24, 2.50, 2.06, etc.) indicates... Diameter of each wire in mm. Let us consider *19/2.50 stranded conductor :*

No. of wires at the centre = 1

No. of wires in the first layer = 6

No. of wires in the second layer = 12

Total no. of layer, $n = 2$

Total no. of wires in the strand $= 1 + 3n(1 + n)$

$= 1 + 3 \times 2(1 + 2) = 1 + 18 = 19$

Overall diameter of the stranded conductor

$= (1 + 2n)d = (1 + 2 \times 2)\ 2.50$

$= 5 \times 2.50 = 12.50$ mm

Fig. 12.2 shows the cross-section of 19/2.50 stranded conductor, Figs. 12.3 and 12.4 show *circular stranded conductors and compact circular stranded conductors respectively.* The former require more insulating and protective materials than those required by the latter. Overall dimensions of compacted conductors become less as is evident from the Fig. 12.4.

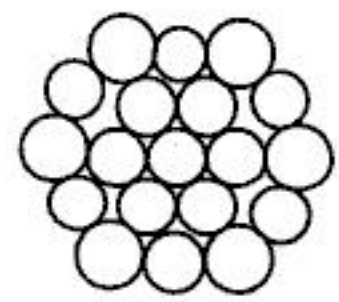

Fig. 12.2. 19/2.50 stranded conductor.

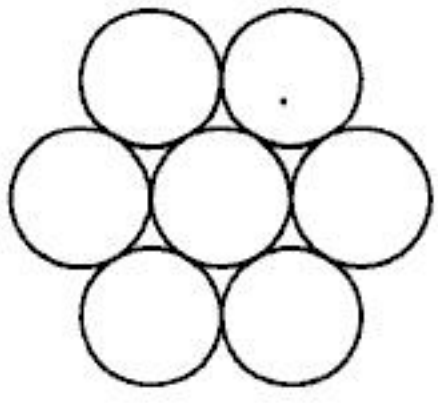

Fig. 12.3. Circular stranded conductor.

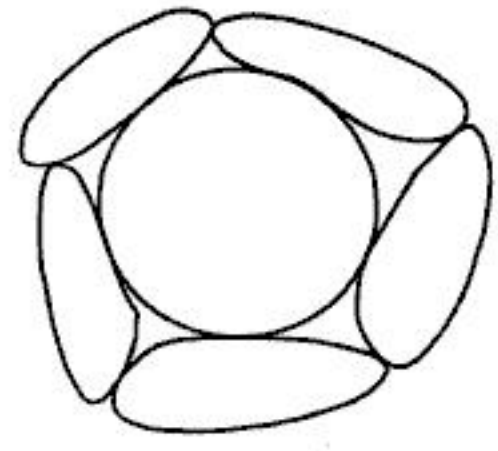

Fig. 12.4. Compact circular stranded conductor.

- *Circular stranded conductors are normally used for single-phase system.*
- *Compact circular stranded conductors are employed in the manufacture of cables.*

Example 12.1. *A 132 kV, 3-phase, 3-wire transmission line transmits over a distance of 144 km an electric power of 36 MW at a p.f. of 0.8 lagging, with an efficiency of 90%. Calculate the weight of material required for the following metallic conductors :*

(i) Copper having resistivity of 1.78×10^{-8} Ω-m and specific gravity 8.9, and

(ii) Aluminium having resistivity of 2.6×10^{-8} Ω-m and specific gravity of 2.

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4. Synthetic resin :

- Synthetic insulators contain compounds of silicon, rubber, resin etc.
- These insulators have high strength and lower weight. Leakage current is higher and longevity is low.
- They are comparatively cheaper.
- These insulators are used in various indoor applications. They are extensively used as bushings.

12.5.3. Types of Insulators

Transmission line insulators may be *classified* as follows :

1. Pin type insulators
2. Suspension type insulators
3. Strain type insulators
4. Shackle insulators.

1. Pin type insulators. Refer to Fig. 12.9.

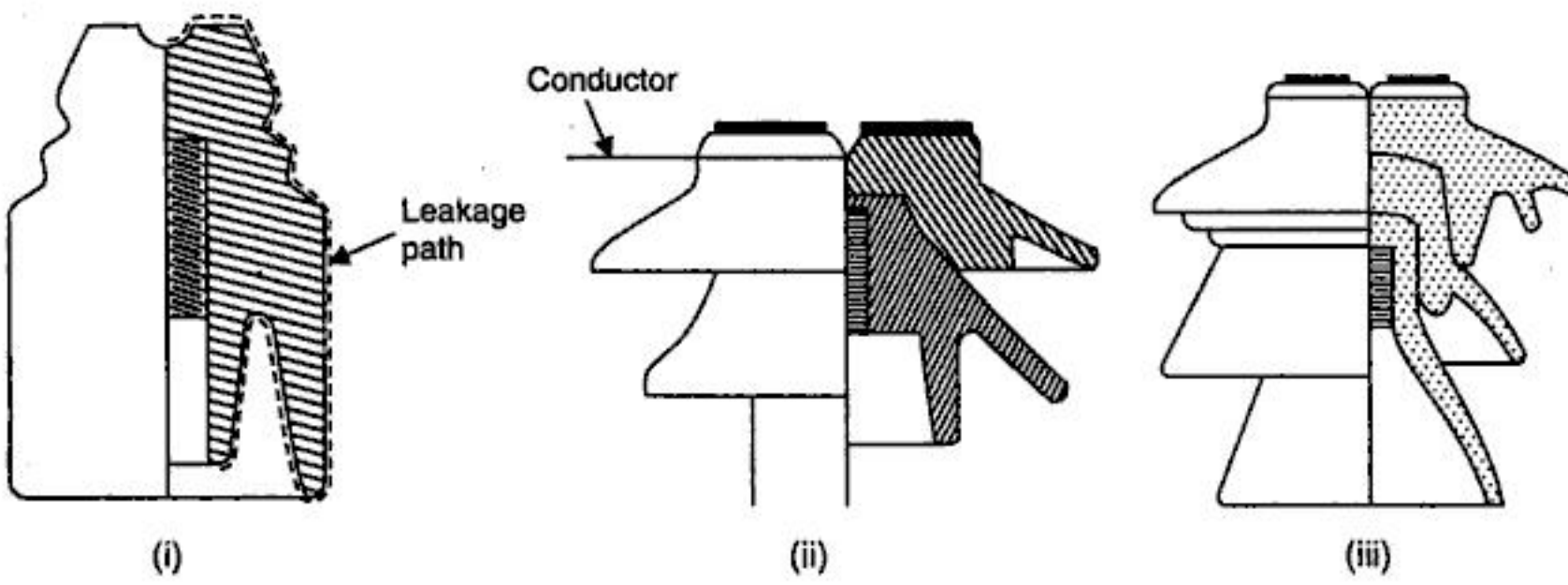

Fig. 12.9. Pin type insulator : (*i*) 11 kV ; (*ii*) 22 kV ; (*iii*) 66 kV.

- As the name suggests, the pin type insulator is designed to be mounted on a pin which in turn is installed on the cross-arm of the pole. The insulator is screwed on the pin and electrical conductor is placed in the groove at the top of the insulator and is tied down with soft copper or soft aluminium binding wire according to material of the conductor.
- For low voltages, pin type insulators made of *glass* are generally used. Pin type insulators made of *porcelain* are designed for voltages upto about 90 kV but are seldom used on lines above 60 kV.

2. Suspension type insulators :

- Since the cost of pin type insulator increases rapidly as the working voltage is increased therefore, this type of insulator is not economical beyond 33 kV. For voltages higher than 33 kV, it is a usual practice to use suspension type insulators as shown in Fig. 12.10.
- The suspension insulator hangs from the cross arm, as opposed to the pin insulator which sits on the top of it. The line conductor is attached to its lower end. These insulators consists of *a number of porcelain discs connected in series by metal links in the form of a "string"*. The number of insulators comprising a string depends upon the following *factors* : (*i*) Working voltage, (*ii*) Type of transmission construction, (*iii*) Size of the insulator used, and (*iv*) Weather conditions.

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Solution. Let C be the capacitance to ground of each unit, then capacitance of the top unit is mC *i.e.* 10 C (where $m = 10$).

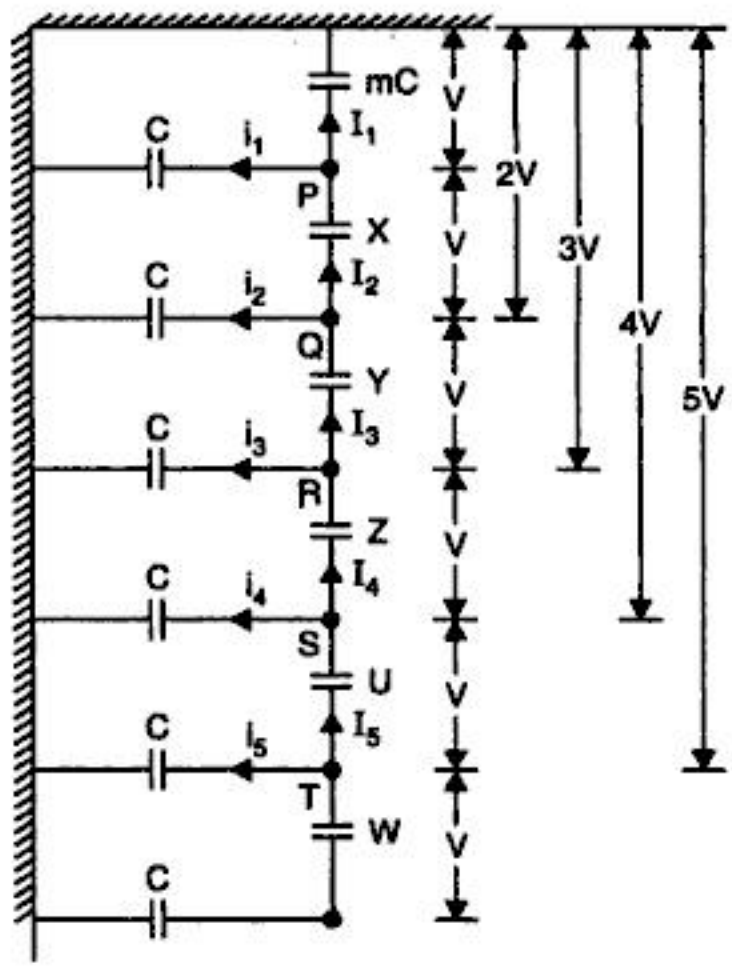

Fig. 12.19

At anode P : $I_2 = I_1 + i_1$

$VX = VmC + VC$

$X = C(1 + m) = C + mC$

At anode Q : $I_3 = I_2 + i_2$

$VY = VX + 2VC$

or, $Y = X + 2C = C(1 + m) + 2C$

$= (1 + 2 + m)C = (1 + 2)C + mC$

At anode R : $I_4 = I_3 + i_3$

$VZ = VY + 3VC$

or, $Z = Y + 3C = (1 + 2 + 3 + m)C$

$= (1 + 2 + 3)C + mC$

At anode S : $I_5 = I_4 + i_4$

$VU = VZ + 4VC$

or, $U = Z + 4C = (1 + 2 + 3 + 4 + m)C$

$= (1 + 2 + 3 + 4)C + mC$

and so on, in general, $C_n = [1 + 2 + 3 + ... + (n - 1)C] + mC$

It is given that $m = 10$

$\therefore$ $X = C + 10C = \mathbf{11\ C}$;

$Y = (1 + 2)C + 10 \times C = \mathbf{13\ C}$;

$Z = (1 + 2 + 3)C + 10C = \mathbf{16\ C}$;

$U = (1 + 2 + 3 + 4)C + 10C = \mathbf{20\ C}$;

$W = (1 + 2 + 3 + 4 + 5)C + 10C = \mathbf{25\ C}$. **(Ans.)**

Example 12.7. *In a 5 insulator disc string capacitance between each unit and earth is 1/6 of the mutual capacitance.*

(i) Find the voltage distribution a cross each insulator in the string as %age of voltage of the conductor to earth.

(ii) Find string efficiency. How is this efficiency affected by rain ?

(iii) If the insulators in the string are designed each to withstand 35 kV maximum (peak), find the operating voltage of the line where 5 suspension insulators string can be used.

Solution. No. of discs = 5

Mutual capacitance of each unit = C

Capacitance between each unit and earth = C_1

$$K = \frac{C_1}{C} = \frac{C_1}{6C_1} = \frac{1}{6} \qquad (\because \quad C = 6C_1 \ldots \textit{Given})$$

(*i*) Voltage distribution across each insulator :

We know that at any node X in case of a string of insulators,

$$V_{x+1} = V_x + KV_x$$

i.e., $V_{1+1} = V_1 + KV_1$

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(*b*) Fig. 12.22 shows the arrangement of a string of three insulators *using guard ring.*

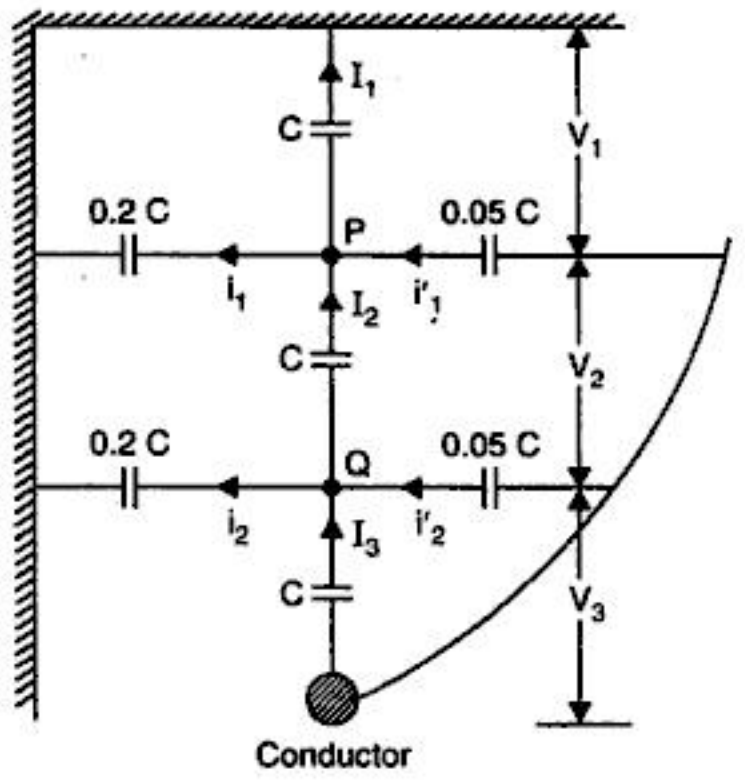

Fig. 12.22

Let V_1, V_2 and V_3 be the voltages across the discs as shown in the figure.

Applying *KCL* at node *P*, we get

$$I_2 + i''_1 = I_1 + i_1$$

or $$V_2\omega C + (V_2 + V_3)\omega \times 0.05C = V_1\omega C + 0.2V_1\omega C$$

or $$V_2 + (V_2 + V_3) \times 0.05 = V_1 + 0.2V_1 = 1.2V_1$$

or $$1.2V_1 - 1.05V_2 - 0.05V_3 = 0 \quad \ldots(i)$$

Applying *KCL* at node *Q*, we have

$$I_3 + i''_2 = I_2 + i_2$$

or $$V_3\omega C + 0.05\, V_3\omega C = V_2\omega C + (V_1 + V_2) \times 0.2C$$

or $$V_3 + 0.05V_3 = V_2 + (V_1 + V_2) \times 0.2$$

or $$0.2V_1 + 1.2V_2 - 1.05V_3 = 0 \quad \ldots(ii)$$

There are three unknowns and two equations only. Hence we divide both the equations by V_3 and rewrite them as

$$1.2x - 1.05y = 0.05 \quad \text{or} \quad 12x - 10.5y = 0.5 \quad \ldots(1)$$

and $$0.2x + 1.2y = 1.05 \quad \text{or} \quad 2x + 12y = 10.5 \quad \ldots(2)$$

where $x = \dfrac{V_1}{V_3}$, and $y = \dfrac{V_2}{V_3}$.

Multiplying eqn. (2) by 6 and subtracting from eqn. (1), we have

$$-82.5y = -62.5$$

$$\therefore \quad y = \frac{62.5}{82.5} = 0.757 = \frac{V_2}{V_3}$$

and $$2x + 12 \times 0.757 = 10.5$$

$$\therefore \quad x = 0.71 = \frac{V_1}{V_3}$$

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stress between the conductors. Thus flash-over possibility is reduced and there is an improvement in the system performance.

2. The effects of transients produced by surges are reduced.

Disadvantages :

1. There is a loss of power (more prominent under abnormal weather conditions) which affects transmission efficiency of the line.
2. Due to corona formation ozone gas is produced which chemically reacts with the conductor and causes corrosion.
3. Due to non-sinusoidal corona current there is a non-sinusoidal voltage drop which may cause some interference with neighbouring communication circuits due to electromagnetic and electrostatic induction.
4. Due to the distortion of wave form, the harmonics (predominantly 3rd harmonic) are introduced into the transmission line. These harmonics increase corona loss.

12.9.5. Corona Loss and its Control

The following *points* relating to corona loss are important :

1. Corona loss is a function of *frequency* ; the higher the frequency of the supply the higher are corona losses. Thus *D.C. corona loss is less as compared with A.C. corona.*

2. When transmission lines are *irregularly spaced*, the surface gradients of the conductors and hence the corona losses if any are *unequal.*

3. Corona loss (a function of air density correction factor) is *more on hilly areas than on plain areas.*

4. Corona loss is *increased during bad atmospheric conditions* (rains, snow, hailstorm etc.) due to reduced critical disruptive voltage.

5. *Larger the size of the conductor, lower is the corona loss.*

6. By bundling the conductors the self GMD (Geometric Mean Diameter) of the conductors is increased thereby, the critical disruptive voltage is *increased* and hence corona loss is *reduced.*

7. Because of *field uniformity in case of cylindrical conductor*, the corona loss is *less*, as compared to any other shape.

8. Flow of load current increases the temperature of conductor. Thus it *prevents* deposition of dew or snow on conductor's surface. This reduces corona loss.

Control of corona loss :

Corona loss can be *reduced* as follows :

(*i*) By using *large diameter conductors* (*ii*) By using *hollow conductors* ;

(*iii*) By using *bundled conductors.*

Note. A typical transmission line may have a fair weather loss of 1 kW per 3-phase mile and foul weather loss of 20 kW per 3-phase mile.

12.9.6. Important Terms Relating to Corona

1. Critical disruptive voltage :

Critical disruptive voltage *is defined as* the *voltage at which complete disruption of dielectric occurs*. This voltage corresponds to the gradient at the surface equal to breakdown strength of air.

Consider two parallel conductors, each of radius r cm and separated by distance D cm. If V is the phase-neutral potential, then potential gradient at the surface of the conductor is given by,

$$g = \frac{V}{r \ln\left(\frac{D}{r}\right)} \text{ volts/cm} \qquad \ldots(12.8$$

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Similarly flux linkages with conductor A due to current I_C flowing in conductor C situated at a distance D_{AC}

$$= \frac{\mu_0 I_C}{2\pi} \int_{D_{AC}}^{\infty} \frac{dx}{x} \qquad ...(iii)$$

Flux linkages with conductor A due to current I_N flowing in conductor N situated at a distance D_{AN}

$$= \frac{\mu_0 I_N}{2\pi} \int_{D_{AN}}^{\infty} \frac{dx}{x}$$

Total flux linkages with conductor A,

$$\lambda_{A(t)} = \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right] + \frac{\mu_0 I_B}{2\pi} \int_{D_{AB}}^{\infty} \frac{dx}{x} + \frac{\mu_0 I_C}{2\pi} \int_{D_{AC}}^{\infty} \frac{dx}{x} + ... + \frac{\mu_0 I_N}{2\pi} \int_{D_{AN}}^{\infty} \frac{dx}{x} \text{ Wb-T/m} \qquad ...(13.6)$$

13.2.3. Inductance of 2-wire (1-phase) Transmission Line

Consider a single phase overhead line consisting of two parallel conductors A and B, each of radius r metres and spaced D metres apart ($D >> r$) as shown in Fig. 13.5. Conductors A and B carry the same current (*i.e.* $I_A = I_B$) in magnitude but opposite in direction as one forms the return path for the other.

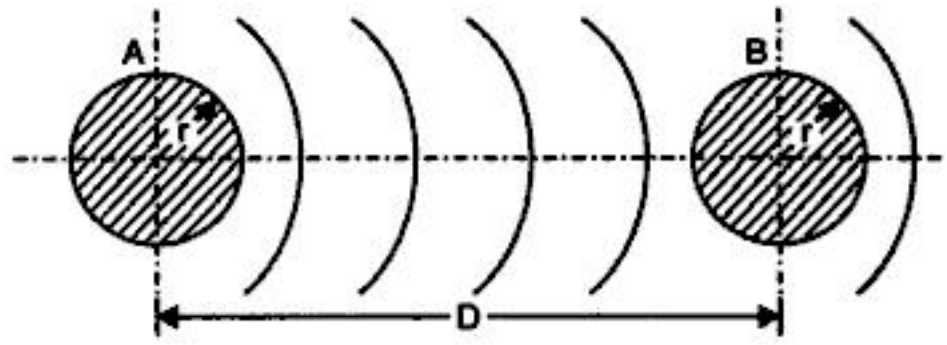

Fig. 13.5. A 1–phase two wire line.

$$\therefore \qquad I_A + I_B = 0$$

Total flux linkages with conductor A,

λ_A = Flux linkages with conductor A due it own current + Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right] + \frac{\mu_0 I_B}{2\pi} \int_D^{\infty} \frac{dx}{x}$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right) I_A + I_B \int_D^{\infty} \frac{dx}{x}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \ln \infty - \ln r\right) I_A + (\ln \infty - \ln D)\, I_B\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + \ln \infty\,(I_A + I_B) - I_A \ln r - I_B \ln D\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A \ln r - I_B \ln D\right] \qquad [\because\ I_A + I_B = 0]$$

Now, $\quad I_A + I_B = 0 \quad$ or $\quad -I_B = I_A$

$$\therefore \qquad -I_B \ln d = I_A \ln D$$

$$\therefore \qquad \lambda_A = \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \ln D - I_A \ln r\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \ln\left(\frac{D}{r}\right)\right]$$

$$= \frac{\mu_0 A}{2\pi}\left[\frac{1}{4} + \ln \frac{D}{r}\right] \text{ Wb-T/m}$$

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or, $$L_A = 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt{D_{AB}\,D_{CA}}}{r}\right) + j1.732\ln\left(\frac{D_{AB}}{D_{CA}}\right)\right] \text{H/m} \quad ...(13.13)$$

[**Note.** *The imaginary part of the flux-linkage or inductance represents exchange of energy between phases.*]

Similarly, $$L_B = 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt{D_{BC}\,D_{AB}}}{r}\right) + j1.732\ln\left(\frac{D_{BC}}{D_{AB}}\right)\right] \text{H/m, and} \quad ...(13.14)$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt{D_{CA}\,D_{BC}}}{r}\right) + j1.732\ln\left(\frac{D_{CA}}{D_{BC}}\right)\right] \text{H/m} \quad ...(13.15)$$

Inductance of *each line conductor*

$$= \frac{1}{3}(L_A + L_B + L_C)$$

$$= 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt[3]{D_{AB}\,D_{BC}\,D_{CA}}}{r}\right)\right] \text{H/m} \quad ...(13.16)$$

.....after substitution and simplification.

If the formula of inductance of an unsymmetrically spaced transposed line is composed with that of symmetrically placed line, we find that inductance of each line conductor in the two cases will be equal if $D = \sqrt[3]{D_{AB}\,D_{BC}\,D_{CA}}$. The distance D is known as *equivalent equilateral spacing* for unsymmetrically transposed line.

Note. Normally, modern power lines are *not* transposed. The transposition, however, *may be affected in the intermediate switching station.* It is to be noted that the difference in the inductances of the three phases is *negligibly small* due to asymmetrical spacing and the inductance of the untransposed line is taken equal to the average value of the inductance of one phase of the same line correctly transposed.

13.2.5. Self-GMD and Mutual-GMD

The inductance calculations relating to multiconductor arrangements can be amply simplified by the use of *self geometrical mean distance* (self-GMD) and *mutual geometrical mean distance* (mutual-GMD). Self-GMD and mutual-GMD are generally represented by the symbols D_s and D_m respectively, and are duscussed below :

(*i*) **Self-GMD (D_s).** It is also sometimes called *"Geometrical mean radius* (GMR)".

Inductance per conductor per metre length is given by,

$$L = 2 \times 10^{-7}\left(\frac{1}{4} + \ln\frac{D}{r}\right) \quad ...[\text{Eqn. (13.7)}]$$

or, $$L = \left(2 \times 10^{-7} \times \frac{1}{4}\right) + \left(2 \times 10^{-7} \ln\frac{D}{r}\right) \quad ...(i)$$

In the above expression the term $\left[2 \times 10^{-7} \times \left(\frac{1}{4}\right)\right]$ is the inductance due to *flux within the solid conductor.* The concept of self-GMD or GMR is introduced to eliminate this term for several purposes. It can be proved mathematically that for a solid round conductor of radius r, the self-GMD or GMR = $0.7788r$. Using self-GMD the eqn. (*i*) reduces to :

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$$= (180 \times 210 \times 150 \times 180)^{1/4} = 178.7 \text{ cm}$$

Self-GMD, $D_s = (D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$

Here $$D_{aa} = D_{a'a'} = 0.7788r = 0.7788 \times \frac{1.8}{2} = 0.7 \text{ cm}$$

$$D_{aa'} = D_{a'a} = 30 \text{ cm}$$

$\therefore$ $$D_s = (0.7 \times 30 \times 0.3 \times 30)^{1/4} = 4.58 \text{ cm}$$

$\therefore$ $$L = 4 \times 10^{-4} \times \ln\left(\frac{178.7}{4.58}\right) = 1.465 \times 10^{-3} \text{ H/km}$$

$$= \mathbf{1.465 \text{ mH/km.}} \quad \textbf{(Ans.)}$$

Example 13.6. *Fig. 13.13, shows the arrangement of a double-circuit single-phase line. Conductors a, a′ form one connection and conductors b, b′ form return connection. The distance between a and a′ is 80 cm and between a and b is 160 cm. If the diameter of each conductor is 2.2 cm determine the total inductance per km of the line.*

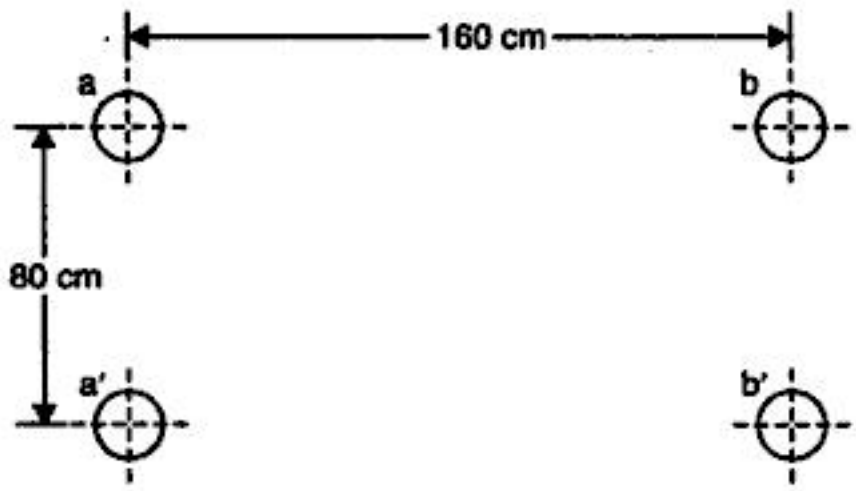

Fig. 13.13

Solution. The conductor radius, $r = \frac{2.2}{2} = 1.1$ cm

GMR of conductor $= 0.7788r = 0.7788 \times 1.1 = 0.8567$ cm

Self-GMD of aa' combination, $D_s = (D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$

$$= (0.8567 \times 80 \times 0.8567 \times 80)^{1/4} = 8.279 \text{ cm}$$

$(\because\ D_{aa} = D_{a'a'} = 0.8567 \text{ cm};\ D_{aa'} = D_{a'a} = 80 \text{ cm})$

Mutual-GMD between a and b,

$$D_m = (D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'})^{1/4}$$

Here $D_{ab} = 160$ cm ; $D_{a'b'} = 160$ cm

$$D_{ab'} = D_{a'b} = \sqrt{(160)^2 + (80)^2} = 178.88 \text{ cm}$$

$\therefore$ $$D_m = (160 \times 178.88 \times 178.88 \times 160)^{1/4} = 169.18 \text{ cm}$$

Loop inductance $= 4 \times 10^{-7} \ln \frac{D_m}{D_s}$ H/m

$$= 4 \times 10^{-7} \ln\left(\frac{169.18}{8.279}\right) = 12.07 \times 10^{-7} \text{ H/m}$$

$\therefore$ Loop inductance per km $= 12.07 \times 10^{-7} \times 10^3 = \mathbf{1.207 \text{ mH/km.}}$ **(Ans.)**

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Further, more the number of conductors in a bundle, the more is the self-GMD. Because of increased GMD line inductance is reduced considerably which results in *increased transmission capacity of the line.*

The *use of bundle conductors entails the following "advantages :*

(*i*) Reduced surge impedance.

(*ii*) Reduced reactance.

(*iii*) Reduced voltage gradient.

(*iv*) Reduced corona loss.

(*v*) Reduced radio interference.

- The *basic difference between a "bundled conductor" and a "composite conductor"* is that the sub-conductors of a bundled conductor are separated from each other by a distance of almost 30 cm or more whereas the wires of a composite conductor touch each other.

(*b*) Refer to Fig. 13.20.

$$D_{14} = D_{24} = D_{25} = D_{35} = \sqrt{(6)^2 + (1.5)^2} = \sqrt{38.25}\ \text{m}$$

$$D_{15} = D_{34} = \sqrt{(6)^2 + (4.5)^2} = 7.5\ \text{m}$$

Mutual-GMD between sides *A* and *B*,

$$D_m = [(D_{14} \times D_{15})(D_{24} \times D_{25})(D_{34} \times D_{35})]^{1/6}$$

$$= [(\sqrt{38.25} \times 7.5)(\sqrt{38.25} \times \sqrt{38.25})(7.5 \times \sqrt{38.25})]^{1/6}$$

$$= [(38.25)^2 \times (7.5)^2]^{1/6} = 6.595\ \text{m}$$

The self-GMD for side *A*,

$$D_{sA} = [(D_{11} \times D_{12} \times D_{13})(D_{21} \times D_{22} \times D_{23})(D_{31} \times D_{32} \times D_{33})]^{1/9}$$

Here, $D_{11} = D_{22} = D_{33} = 0.7788 \times 2.4 \times 10^{-3} = 0.001869\ \text{m}$

Substituting the values, we get

$$D_{sA} = [(0.001869 \times 3 \times 6)(3 \times 0.001869 \times 3)(6 \times 3 \times 0.001869)]^{1/9}$$

$$= [(0.001869)^3 (3)^4 (6)^2]^{1/9} = 0.2989\ \text{m}$$

Similarly, $D_{sB} = [(D_{44} \times D_{45})(D_{54} \times D_{55})]^{1/4}$

where, $D_{44} = D_{55} = 0.7788 \times 4.8 \times 10^{-3} = 0.003738\ \text{m}$

Substituting the values, we get

$$D_{sB} = [(0.003738 \times 3)(3 \times 0.003738)]^{1/4}$$

$$= [(0.003738)^2 (3)^2]^{1/4} = 0.1059\ \text{m}$$

$$\text{Inductance, } \mathbf{L_A} = 2 \times 10^{-7} \ln \left(\frac{D_m}{D_{sA}}\right)$$

$$= 2 \times 10^{-7} \ln \left(\frac{6.595}{0.2989}\right) = 6.188 \times 10^{-7}\ \text{H/m} = 0.6188\ \text{mH/km}$$

$$\text{Inductance, } \mathbf{L_B} = 2 \times 10^{-7} \ln \left(\frac{D_m}{D_{sB}}\right)$$

$$= 2 \times 10^{-7} \ln \left(\frac{6.595}{0.1059}\right) = 8.263 \times 10^{-7}\ \text{H/m} = 0.8263\ \text{mH/km}$$

$\therefore$ *Inductance of complete line*

$$\mathbf{L} = L_A + L_B = 0.6188 + 0.8263 = \mathbf{1.4451\ mH/km.}\quad \textbf{(Ans.)}$$

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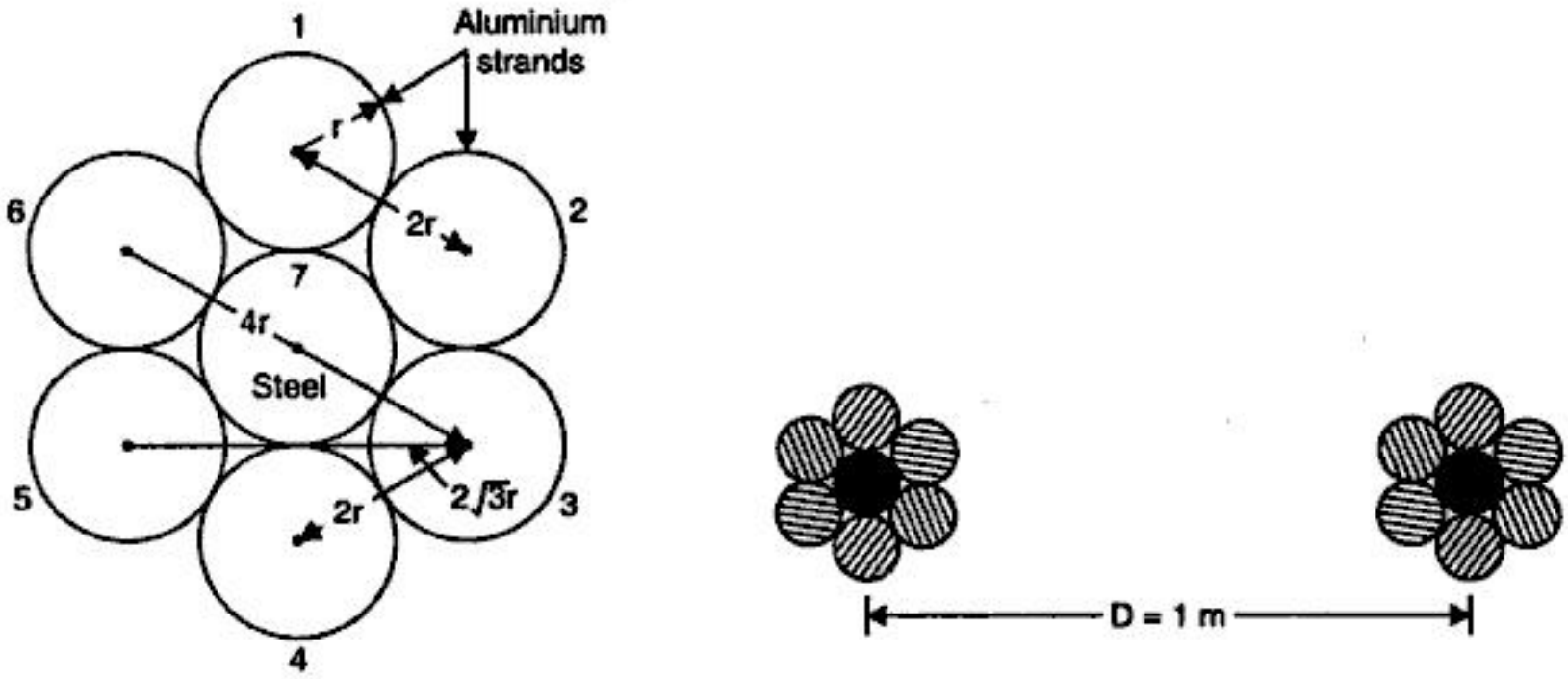

(a) Cross-section of ACSR conductor.

(b) Line consisting of two ACSR conductors.

Fig. 13.24

$$D_{11} = r' = 0.7788r \; ; D_{12} = D_{16} = 2r \; ; D_{13} = D_{15}$$

$$= \sqrt{D_{14}^2 - D_{34}^2} = \sqrt{(4r)^2 - (2r)^2} = 2\sqrt{3}r$$

$$D_{14} = 4r$$

$$D_{s1} = (D_{11} \times D_{12} \times D_{13} \times D_{14} \times D_{15} \times D_{16})^{1/6}$$

$$= (0.7788r \times 2r \times 2\sqrt{3}r \times 4r \times 2\sqrt{3}r \times 2r)^{1/6} = 2.304r$$

$$= D_{s2} = D_{s3} = D_{s4} = D_{s5} = D_{s6}$$

$\therefore$ $$D_s = (D_{s1} \times D_{s2} \times D_{s3} \times D_{s4} + D_{s5} \times D_{s6})^{1/6} = [(2.304r)^6]^{1/6}$$

$$= 2.304r = 2.304 \times 0.0084 = 0.01935 \text{ m}$$

GMD, $D_m = 1$ m (Since $D >> r$)

$\therefore$ The inductance of each conductor,

$$L = 2 \times 10^{-7} \ln \left(\frac{D_m}{D_s} \right)$$

$$= 2 \times 10^{-7} \ln \left(\frac{1}{0.01935} \right) = 7.89 \times 10^{-7} \text{ H/m} \quad \text{or} \quad 0.789 \text{ mH/km}$$

Loop inductance $= 2L = 2 \times 0.789 = 1.578$ mH/km

or, Loop reactance $= 2\pi \times 50 \times 1.578 \times 10^{-3} =$ **0.495 Ω/km. (Ans.)**

13.3. RESISTANCE OF A TRANSMISSION LINE

The *resistance* of transmission line conductors is the *main source of line power loss* (although the contribution of line resistance of series line impedance can be neglected in most cases). Thus, while considering the transmission line economy, the presence of line resistance must be taken into consideration.

$$\text{The effective AC resistance, } R = \frac{\text{Average power loss in conductor (in watts)}}{I^2} \text{ ohms} \qquad ...(13.17)$$

where, I = R.m.s. current in the conductor, amperes

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$$= \frac{1}{2\pi\varepsilon_0}\ [Q_A(\ln\infty - \ln r) + Q_B(\ln\infty - \ln D_{AB}) + Q_C(\ln\infty - \ln D_{AC}) + \ldots\ldots Q_N(\ln\infty - \ln D_{AN})]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{1}{r}\right) + Q_B \ln\left(\frac{1}{D_{AB}}\right) + Q_C \ln\left(\frac{1}{D_{AC}}\right) + \ldots\ldots \ldots\ldots Q_N \ln\left(\frac{1}{D_{AN}}\right) + \ln\infty\,(Q_A + Q_B + Q_C + \ldots\ldots Q_N)\right]$$

$$\left[\because\ -\ln(r) = \ln(r)^{-1} = \ln\left(\frac{1}{r}\right)\right]$$

Assuming balanced conditions *i.e.*, $Q_A + Q_B + Q_C + \ldots\ldots Q_N = 0$, we have

$$V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{1}{r}\right) + Q_B \ln\left(\frac{1}{D_{AB}}\right) + Q_C \ln\left(\frac{1}{D_{AC}}\right) + \ldots\ldots Q_N \ln\left(\frac{1}{D_{AN}}\right)\right] \quad \ldots(13.21)$$

13.5.3. Capacitance of a Single-phase Two-wire Overhead Transmission Line

Consider a single-phase overhead transmission line with two parallel conductors A and B, each of radius r metres placed at a distance D metres in air ($D >> r$). Let Q_1 and Q_2 coulombs per metre length be their respective charges.

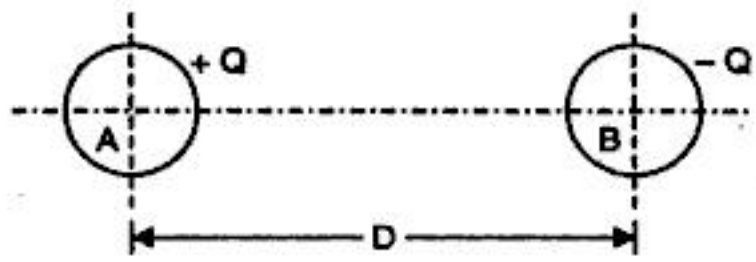

Fig. 13.29

Potential of conductor A,

$$V_A = \int_r^\infty \frac{Q}{2\pi\varepsilon_0}\cdot\frac{dx}{x} + \int_D^\infty \frac{(-Q)}{2\pi\varepsilon_0}\cdot\frac{dx}{x}$$

$$= \frac{Q}{2\pi\varepsilon_0}\ [(\ln\infty - \ln r) - (\ln\infty - \ln D)]$$

$$= \frac{Q}{2\pi\varepsilon_0}\left[\ln\left(\frac{\infty}{r}\right) - \ln\left(\frac{\infty}{D}\right)\right] = \frac{Q}{2\pi\varepsilon_0}\ln\left(\frac{D}{r}\right) \text{ volts}$$

Similarly, potential of conductors B,

$$V_B = \int_r^\infty \frac{-Q}{2\pi\varepsilon_0}\cdot\frac{dx}{x} + \int_D^\infty \frac{Q}{2\pi\varepsilon_0}\cdot\frac{dx}{x}$$

$$= \frac{-Q}{2\pi\varepsilon_0}\left[\ln\left(\frac{\infty}{r}\right) - \ln\left(\frac{D}{r}\right)\right] = \frac{-Q}{2\pi\varepsilon_0}\ln\frac{D}{r} \text{ volts}$$

Potential difference between conductor A and B,

$$V_{AB} = V_A - V_B = \frac{Q}{2\pi\varepsilon_0}\ln\left(\frac{D}{r}\right) - \left[\left(\frac{-Q}{2\pi\varepsilon_0}\right)\ln\left(\frac{D}{r}\right)\right]$$

or,
$$V_{AB} = \frac{Q}{\pi\varepsilon_0}\ln\left(\frac{D}{r}\right) \text{ volts} \quad \ldots(13.22)$$

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Similarly, $$V_B = \frac{1}{2\pi\varepsilon_0}\left[Q_B \ln\left(\frac{1}{r}\right) + Q_C \ln\left(\frac{1}{D_{BC}}\right) + Q_A \ln\left(\frac{1}{D_{AB}}\right)\right] \quad ...(ii)$$

and, $$V_C = \frac{1}{2\pi\varepsilon_0}\left[Q_C \ln\left(\frac{1}{r}\right) + Q_A \ln\left(\frac{1}{D_{CA}}\right) + Q_B \ln\left(\frac{1}{D_{BC}}\right)\right] \quad ...(iii)$$

Substituting $Q_C = -(Q_A + Q_B)$ in (i) and (ii), we get

$$V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{1}{r}\right) + Q_B \ln\left(\frac{1}{D_{AB}}\right) - (Q_A + Q_B)\ln\left(\frac{1}{D_{CA}}\right)\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{D_{CA}}{r}\right) + Q_B \ln\left(\frac{D_{CA}}{D_{AB}}\right)\right] \quad ...(iv)$$

and, $$V_B = \frac{1}{2\pi\varepsilon_0}\left[Q_B \ln\left(\frac{1}{r}\right) - (Q_A + Q_B)\ln\left(\frac{1}{D_{BC}}\right) + Q_A \ln\left(\frac{1}{D_{AB}}\right)\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{D_{BC}}{D_{AB}}\right) + Q_B \ln\left(\frac{D_{BC}}{r}\right)\right] \quad ...(v)$$

Multiplying (iv) by $\ln\left(\frac{D_{BC}}{r}\right)$ and (v) by $\ln\left(\frac{D_{CA}}{D_{AB}}\right)$, we get

$$V_A \ln\left(\frac{D_{BC}}{r}\right) = \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{D_{CA}}{r}\right).\ln\left(\frac{D_{BC}}{r}\right) + Q_B \ln\left(\frac{D_{CA}}{D_{AB}}\right).\ln\left(\frac{D_{BC}}{r}\right)\right] \quad ...(vi)$$

and, $$V_B \ln\left(\frac{D_{CA}}{D_{AB}}\right) = \frac{1}{2\pi\varepsilon_0}\left[Q_A \ln\left(\frac{D_{BC}}{D_{AB}}\right)\ln\left(\frac{D_{CA}}{D_{AB}}\right) + Q_B \ln\left(\frac{D_{BC}}{r}\right).\ln\left(\frac{D_{CA}}{D_{AB}}\right)\right] \quad ...(vii)$$

Subtracting (vii) from (vi), we get

$$V_A \ln\left(\frac{D_{BC}}{r}\right) - V_B \ln\left(\frac{D_{BC}}{D_{AB}}\right) = \frac{Q_A}{2\pi\varepsilon_0}\left[\ln\left(\frac{D_{CA}}{r}\right)\ln\left(\frac{D_{BC}}{r}\right) - \ln\left(\frac{D_{BC}}{D_{AB}}\right).\ln\left(\frac{D_{CA}}{D_{AB}}\right)\right]$$

or, $$Q_A = 2\pi\varepsilon_0\left[\frac{V_A \ln\left(\frac{D_{BC}}{r}\right) - V_B \ln\left(\frac{D_{CA}}{D_{AB}}\right)}{\ln\left(\frac{D_{CA}}{r}\right)\ln\left(\frac{D_{BC}}{r}\right) - \ln\left(\frac{D_{BC}}{D_{AB}}\right)\ln\left(\frac{D_{CA}}{D_{AB}}\right)}\right] \quad ...(viii)$$

Capacitance of conductor A,

$$C_A = \frac{Q_A}{V_A} = 2\pi\varepsilon_0\left[\frac{\ln\left(\frac{D_{BC}}{r}\right) - \frac{V_B}{V_A}\ln\left(\frac{D_{CA}}{D_{AB}}\right)}{\ln\left(\frac{D_{CA}}{r}\right)\ln\left(\frac{D_{BC}}{r}\right) - \ln\left(\frac{D_{BC}}{D_{AB}}\right)\ln\left(\frac{D_{CA}}{D_{AB}}\right)}\right] \text{ F/m} \quad ...(13.28)$$

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$$= \frac{-Q}{2\pi\varepsilon_0}\left[-\ln(r) + \ln(D) + \ln(2h) - \ln\left(\sqrt{4h^2 + D^2}\right)\right]$$

or, $$V_B = \frac{(-Q)}{2\pi\varepsilon_0} \ln\left[\frac{2hD}{r\sqrt{4h^2 + D^2}}\right] \text{ volts} \qquad ...(ii)$$

Potential difference between the conductors A and B,

$$V_{AB} = V_A - V_B = \frac{Q}{2\pi\varepsilon_0} \ln\left[\frac{2hD}{r\sqrt{4h^2 + D^2}}\right] - \frac{-Q}{2\pi\varepsilon_0} \ln\left[\frac{2hD}{r\sqrt{4h^2 + D^2}}\right]$$

or, $$V_{AB} = \frac{Q}{\pi\varepsilon_0} \ln\left[\frac{2hD}{r\sqrt{4h^2 + D^2}}\right]$$

$$= \frac{Q}{\pi\varepsilon_0} \ln\left[\frac{2hD}{r \times 2h\sqrt{1 + (D^2/4h^2)}}\right] = \frac{Q}{\pi\varepsilon_0} \ln\left[\frac{D}{r\sqrt{1 + (D^2/4h^2)}}\right] \text{ volts}$$

$\therefore$ Capacitance between conductors A and B,

$$C_{AB} = \frac{Q}{V_{AB}} = \frac{Q}{\frac{Q}{\pi\varepsilon_0} \ln\left[\frac{D}{r\sqrt{1 + (D^2/4h^2)}}\right]} = \frac{\pi\varepsilon_0}{\ln\left[\frac{D}{r\sqrt{1 + (D^2/4h^2)}}\right]} \text{ F/m line-to-line}$$

...(13.35)

$$C_N = \frac{2\pi\varepsilon_0}{\ln\left[\frac{D}{r\sqrt{1 + (D^2/4h^2)}}\right]} \text{ F/m to neutral} \qquad ...(13.35\,a)$$

From eqn. [13.35 (a)] it may be observed that the presence of earth modifies radius r to $r\sqrt{1 + (D^2/4h^2)}$. Since normally h is large compared to D, the effect of earth on line capacitance is *negligible*.

A similar treatment can be adopted for 3-phase transmission lines.

Example 13.18. *A single-phase overhead transmission line consists of two parallel straight conductors spaced 2.5 metres apart. The radius of each conductor is 1.2 cm. Calculate the capacitance of the line per km. Given that* $\varepsilon_0 = 8.854 \times 10^{-12}$ *F/m.*

Solution. *Given :* $r = 1.2$ cm $= 0.012$ m ; $D = 2.50$ cm ; $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

Capacitance of the line, $\mathbf{C} = \frac{\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)}$ F/m ...[Eqn. (13.23)]

$$= \frac{\pi \times 8.854 \times 10^{-12}}{\ln\left(\frac{2.5}{0.012}\right)} = 5.21 \times 10^{-12} \text{ F/m}$$

$$= 5.21 \times 10^{-9} \text{ F/km} = \mathbf{0.00521\mu\ F/m.} \quad \textbf{(Ans.)}$$

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Example 13.25. *Derive an expression for the charge (complex) value per metre length of conductor of an untransposed three phase line shown in Fig. 13.40. The applied voltage is balanced three phase, 50 Hz. Take the voltage of phase-a as reference phasor. All conductors have the same radii. Also find the charging current of phase-a. Neglect the effect of ground.*

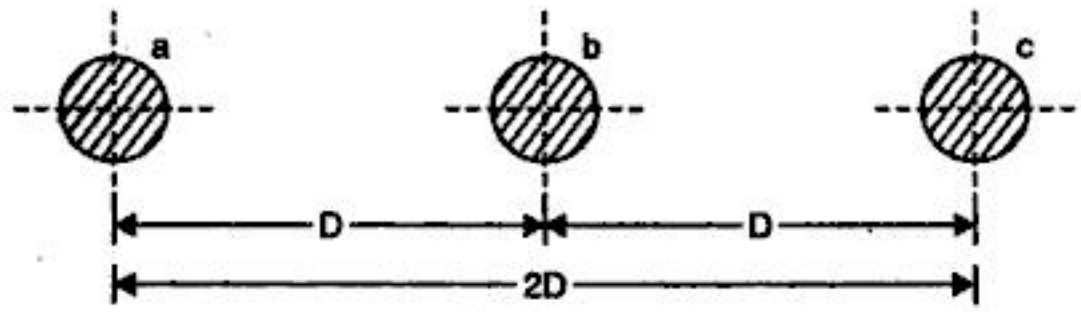

Fig. 13.40

Solution. Let Q_1, Q_2 and Q_3 coulombs per metre be charges on the respective conductors a, b and c (due to the applied balanced voltage on each conductor).

The potential of conductor a is equal to work done to bring a unit charge from infinity to the surface of the conductor, but as the unit charge is brought from infinity the work will have to be done against the electrostatic forces due to charges Q_2 and Q_3 on conductors b and c respectively.

$\therefore$ The work done to bring the unit charge from infinity to the surface of conductor a (at that instant the distances of the unit charge from b and c are D and $2D$)

$$= \int_r^\infty \frac{Q_1}{2\pi\varepsilon_0 x}\,dx + \int_D^\infty \frac{Q_2}{2\pi\varepsilon_0 x}\,dx + \int_{2D}^\infty \frac{Q_3}{2\pi\varepsilon_0 x}\,dx$$

$\therefore$
$$V_1 = \int_r^\infty \frac{Q_1}{2\pi\varepsilon_0 x}\,dx + \int_D^\infty \frac{Q_2}{2\pi\varepsilon_0 x}\,dx + \int_{2D}^\infty \frac{Q_3}{2\pi\varepsilon_0 x}\,dx$$

or,
$$V_1 = \frac{1}{2\pi\varepsilon_0}\left[Q_1 \log_e \frac{\infty}{r} + Q_2 \log_e \frac{\infty}{D} + Q_3 \log_e \frac{\infty}{2D}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[-Q_1 \ln (r) - Q_2 \ln (D) - Q_3 \ln (2D) + \ln \infty (Q_1 + Q_2 + Q_3)\right]$$

Since, $Q_1 + Q_2 + Q_3 = 0$,

$\therefore$
$$V_1 = \frac{1}{2\pi\varepsilon_0}\left[Q_1 \ln \frac{1}{r} + Q_2 \ln \frac{1}{D} + Q_3 \ln \frac{1}{2D}\right]$$

Similarly,
$$V_2 = \frac{1}{2\pi\varepsilon_0}\left[Q_1 \ln \frac{1}{D} + Q_2 \ln \frac{1}{r} + Q_3 \ln \frac{1}{2D}\right]$$

and,
$$V_3 = \frac{1}{2\pi\varepsilon_0}\left[Q_1 \ln \frac{1}{2D} + Q_2 \ln \frac{1}{D} + Q_3 \ln \frac{1}{r}\right]$$

Putting $Q_3 = -(Q_1 + Q_2)$, we have

$$V_1 = \frac{1}{2\pi\varepsilon_0}\left[Q_1 \ln \frac{1}{r} + Q_2 \ln \frac{1}{D} + (Q_1 + Q_2) \ln \frac{1}{2D}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_1 \ln \frac{1}{r} + Q_2 \ln \frac{1}{D} - Q_1 \ln \frac{1}{2D} - Q_2 \ln \frac{1}{2D}\right]$$

$$= \frac{1}{2\pi\varepsilon_0} Q_1 \left[\ln \frac{1}{r} - \ln \frac{1}{2D}\right] + Q_2 \left[\ln \frac{1}{D} - \ln \frac{1}{2D}\right]$$

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(*ii*) *Unsymmetrical spacing* (Transposed conductors) :

$$L_A = 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt{D_{AB}\,D_{CA}}}{r}\right) + j\,1.732\ln\left(\frac{D_{AB}}{D_{CA}}\right)\right] \text{ H/m}$$

$$L_B = 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt{D_{BC}\,D_{AB}}}{r}\right) + j\,1.732\ln\left(\frac{D_{BC}}{D_{AB}}\right)\right] \text{ H/m}$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt{D_{CA}\,D_{BC}}}{r}\right) + j\,1.732\ln\left(\frac{D_{CA}}{D_{BC}}\right)\right] \text{ H/m}$$

Inductance of each line conductor $= \dfrac{L_A + L_B + L_C}{3}$

$$= 10^{-7}\left[\frac{1}{2} + 2\ln\left(\frac{\sqrt[3]{D_{AB} \times D_{BC} \times D_{CA}}}{r}\right)\right] \text{ H/m}$$

3. Self-GMD or GMR = 0.7788 r.
4. Mutual-GMD represents the equivalent geometrical spacing.
5. The tendency of alternating current to concentrate near the surface of a conductor is known as *skin effect.*
6. The alternating magnetic flux in a conductor caused by the current flowing in a neighbouring conductor gives rise to circulating current which causes an apparent increase in the resistance of a conductor. This phenomenon is called *proximity effect.*
7. *Important formulate for "capacitance"* :

(*i*) *Capacitance of a single phase two-wire line* :

$$C = \frac{\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)} \text{ F/m}$$

$$C_N = \frac{2\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)} \text{ F/m}$$

(*ii*) *Capacitance of a 3-phase line* :

(*a*) *Symmetrical spacing* :

$$C_A = \frac{2\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)} \; (= C_B = C_C)$$

(*b*) *Unsymmetrical spacing with transposed conductors* :

$$C_A = \frac{2\pi\varepsilon_0}{\ln\left[\frac{(D_{12}D_{23}D_{31})^{1/3}}{r}\right]} \; (= C_B = C_C)$$

(*iii*) Effect of earth on the capacitance of single-phase transmission lines :

$$C_{AB} = \frac{\pi\varepsilon_0}{\ln\left[\frac{D}{r\sqrt{1+(D^2/4h^2)}}\right]} \text{ F/m line-to-line}$$

$$C_N = 2\,C_{AB} \text{ F/m to neutral}$$

where, D = Distance between the conductors, and
h = Height of the conductor above the ground.

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14.4.3. Effect of Load Power Factor on Efficiency and Regulation of a Transmission Line

Effect of load power factor on efficiency of the line :

When given power at a given voltage is delivered to the consumer, the line current is inversely proportional to the power factor of the load ($P = V_R I \cos \phi_R$ or $I = \dfrac{P}{V_R \cos \phi_R}$ for a single-phase line, or $I = \dfrac{P}{3V_R \cos \phi_R}$ for a 3-phase line). Thus, the current and hence power loss in the line goes on increasing as the power factor goes or decreasing. Hence the *"efficiency" of the line decreases with the fall in power factor* and vice versa.

Effect of load power factor on regulation of the short-line :

$$\% \text{ Regulation} = \frac{V_S - V_R}{V_R} \times 100$$

where V_S and V_R are the magnitudes of the no-load and full-load receiving end voltages respectively, at a specified power factor (In a short line V_s is equal to the no-load receiving end voltage).

or,
$$\% \text{ Regulation} = \frac{IR \cos \phi_R + IX \sin \phi_R}{V_R} \qquad ...(i)$$

In the above equation ϕ_R has been considered + *ve* for *lagging load*. It will be – *ve* for *leading load*,

$$\% \text{ Regulation} = \frac{IR \cos \phi_R - IX \sin \phi_R}{V_R} \times 100 \qquad ...(ii)$$

Voltage regulation becomes negative *i.e.* load voltage is more than no-load voltage when in equation (*ii*)

$$X \sin \phi_R > R \cos \phi_R \qquad \text{or} \qquad \tan \phi_R \text{ (leading)} > \frac{R}{X}$$

From eqn. (*ii*) it follows that for zero voltage regulation,

$$\tan \phi_R \fallingdotseq \frac{R}{X} = \cot \theta$$

i.e.
$$\phi_R \text{ (leading)} = \frac{\pi}{2} - \theta \qquad ...(iii)$$

where θ is the angle of the transmission line impedance. This is, however, an approximate condition. The *exact condition for zero regulation is determined as follows :*

The phasor diagram under conditions of zero voltage regulation is shown in Fig. 14.5.

Here, $V_S = V_R$

$OC = OA$

$$\sin \angle AOD = \frac{AD}{OA} = \frac{AC/2}{OA} = \frac{(IZ/2)}{V_R}$$

$$\angle AOD = \sin^{-1}\left(\frac{IZ}{2V_R}\right)$$

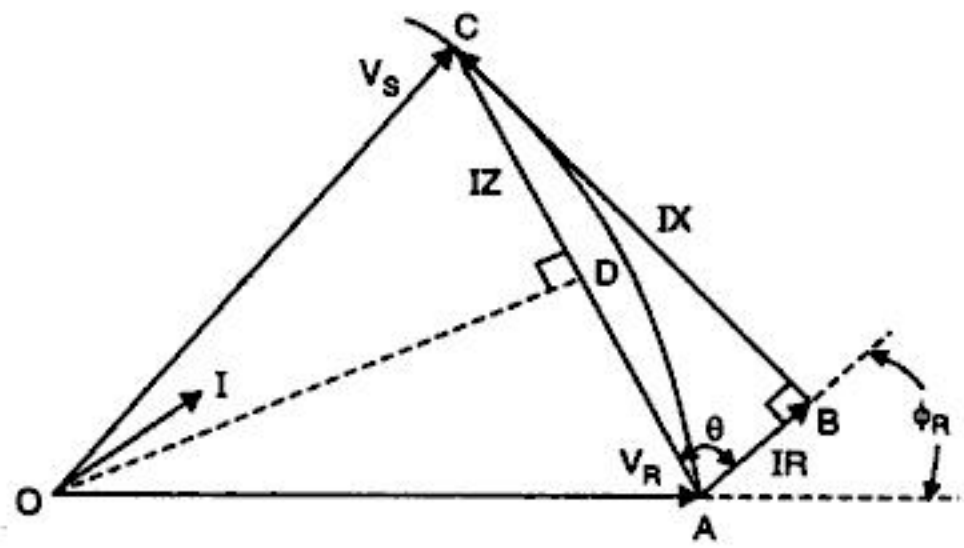

Fig. 14.5. Phasor diagram for zero regulation condition.

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Length of the line, l :

Load current, $$I = \frac{P}{\sqrt{3}\, V_{RL} \cos \phi_R} = \frac{16000}{\sqrt{3} \times 132 \times 0.8} = 87.48 \text{ A}$$

$$\text{Line losses} = 3I^2R = 8.5\% \text{ of } 16000 = 1360 \text{ kW}$$

or, $$R = \frac{1360 \times 1000}{3 \times (87.48)^2} = 59.24\ \Omega$$

$\therefore$ Length of line, $l = \frac{59.24}{1.2} =$ **49.4 km. (Ans.)**

Example 14.6. *A short 3-phase transmission line connected to a 33 kV, 50 Hz, generating station at the sending end is required to supply a load of 10 MW at 0.8 lagging power factor at 30 kV at the receiving end. If the minimum transmission efficiency is limited to 96 percent determine the per phase values of resistance and inductance of the line.* **(AMIE)**

Solution. *Given* : $V_{SL} = 33$ kV ; $f = 50$ Hz ; $P = 10$ MW $= 10000$ kW ; $\cos \phi_R = 0.8$ lagging $V_{RL} = 30$ kV ; $\eta_r = 96\%$.

R, L per phase :

Phase voltage at the receiving end, $V_R = \frac{30 \times 1000}{\sqrt{3}} = 17320$ V

Line current, $$I = \frac{P}{3V_R \cos \phi_R} = \frac{10000 \times 1000}{3 \times 17320 \times 0.8} = 240.57 \text{ A}$$

$$\text{Power sent out} = \frac{\text{Power delivered}}{\eta_T} = \frac{10000}{0.96} = 104.17 \text{ kW}$$

$$\text{Line losses} = \frac{3I^2R}{1000} = 10417 - 10000 = 417 \text{ kW}$$

$\therefore$ $$R = \frac{417 \times 1000}{3 \times (240.57)^2} =$$ **2.4Ω/phase. (Ans.)**

Phase voltage at the sending end, $V_S = \frac{V_{SL}}{\sqrt{3}} = \frac{33000}{\sqrt{3}} = 19052$ V

Also, $$V_S = V_R + IR \cos \phi_R + I X \sin \phi_R \text{ (app.)}$$

or, $$19052 = 17320 + 240.57 \times 2.4 \times 0.8 + 240.57 \times X \times 0.6 = 17781.9 + 144.3X$$

or, $$X = \frac{19052 - 17781.9}{144.3} = 8.8\ \Omega/\text{phase}$$

$\therefore$ $$L = \frac{8.8}{2\pi \times 50} =$$ **0.028 H/phase. (Ans.)**

Example 14.7. *A 3-phase overhead line delivers 4200 kW at a power factor of 0.8 lagging to a load. If the sending end voltage is 33 kV, and resistance and reactance of each conductor are 4.5 Ω and 5.6 Ω respectively, determine :*

(i) The receiving end line voltage.

(ii) Line current.

(iii) Transmission efficiency.

Solution. *Given* : $P = 4200$ kW ; $\cos \phi_R = 0.8$ lagging ; $V_{SL} = 33$ kV ; $R = 4.5\ \Omega$; $X = 5.6\ \Omega$ per conductor.

(i) Receiving end line voltage, V_{RL}

Sending end voltage/phase $V_S = \frac{33000}{\sqrt{3}} = 19052$ V

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$$= 127 + 10^{-3}[5248.6 + j16402 - j3254 + 10168.8]$$
$$= 127 + 10^{-3}\,(15417 + j13148) = (142.42 + j13.15)\text{kV}$$

Charging current, $\bar{I}_C = jY\bar{V}' = j0.001(142.42 + j13.15) \times 10^3$ A
$= (j142.42 - 13.15)$ A

(*i*) Sending end current, $\bar{I}_S$:

$$\bar{I}_S = \bar{I}_R + \bar{I}_C = (262.43 - j162.7) + (j142.42 - 13.15)$$
$$= (249.28 - j20.28) = 250 \angle -4.65°$$

(*ii*) Sending end line voltage, V_{SL} :

$$\bar{V}_S = \bar{V}' + \bar{I}_S \frac{\bar{Z}}{2}$$
$$= (142.42 + j13.15) + (249.28 - j20.28)\left(\frac{40 + j\,125}{2}\right)$$
$$= (142.42 + j13.15) + (249.28 - j20.28)(20 + j62.5) \times 10^{-3}\text{ kV}$$
$$= (142.42 + j13.15) + 10^{-3}(4985.6 + j15580 - j405.6 + 1267.5)$$
$$= (142.42 + j13.15) + 10^{-3}(6253 + j15174) = (148.67 + j28.32)\text{ kV}$$
$$= 151.34 \angle 10.78°\text{ kV}$$

$\therefore$ $V_{SL} = \sqrt{3} \times 151.34 =$ **262.13 kV. (Ans.)**

(*iii*) Sending end power factor, $\cos\phi_S$:

$\cos\phi_S = \cos[10.78° - (-465°)] = \cos 15.43° =$ **0.964. (Ans.)**

(*iv*) Transmission efficiency, η_T :

$$\eta_T = \frac{\text{Receiving end power}}{\text{Sending end power}} = \frac{100 \times 10^3\text{ (kW)}}{3V_S\, I_S \cos\phi_S\text{ (kW)}}$$
$$= \frac{100 \times 10^3}{3 \times 151.34 \times 250 \times 0.964} = 0.914 \quad \text{or} \quad \textbf{91.4\%. (Ans.)}$$

(*v*) Percentage regulation :

$$V_{RO} = \frac{V_S\,(-j/\omega C)}{R/2 + j\,X/2 - j/\omega C} = \frac{151.34\,(-j10^3)}{20 + j62.5 - j10^3} = \frac{151.34\,(-j10^3)}{20 - j\,937.5} = 161.39\text{ kV}$$

$\therefore$ Percentage regulation $= \dfrac{V_{RO} - V_R}{V_R} \times 100 = \dfrac{161.39 - 127}{127} \times 100 =$ **27.08%. (Ans.)**

(*vi*) Surge impedance of the line, Z_{surge} :

Surge impedance of a line is defined as the square root of Z/Y *i.e.* $Z_{surge} = \sqrt{\dfrac{Z}{Y}}$

where, Z = Series impedance ($= R + jX$), and
Y = Shunt admittance.

$\therefore$ $$Z_{surge} = \sqrt{\frac{40 + j125}{j0.001}} = \sqrt{\frac{(40 + j125) \times j0.001}{j0.001 \times j0.001}} = \sqrt{-10^6(j0.04 - 0.125)}$$
$$= 10^3\sqrt{(0.125 - j0.04)} = \textbf{131.24 Ω. (Ans.)}$$

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Receiving end current, $I_R = \dfrac{50 \times 10^6}{\sqrt{3} \times (110 \times 1000) \times 0.8} = 328$ A

Phase voltage at the receiving end, $V_R = \dfrac{110}{\sqrt{3}} = 63.51$ kV

$\cos \phi_R = 0.8$, $\sin \phi_R = 0.6$

Taking phase voltage at the receiving end as the reference phasor, we have

$$\bar{V}_R = 63.51(1 + j0)\text{kV}$$

$$\bar{I}_R = I_R (\cos \phi_R - j \sin \phi_R) = 328(0.8 - j0.6) = (262.4 - j196.8)\text{ A}$$

$$\bar{I}_{CR} = \frac{1}{2} \bar{Y} \bar{V}_R = \frac{1}{2} \times (j\,4.5 \times 10^{-4}) \times 63.51(1 + j0) \times 10^3 = j14.3\text{ A}$$

Line current, $\bar{I}_L = \bar{I}_R + \bar{I}_{CR} = (262.4 - j196.8) + j14.3 = (262.4 - j182.5)$

$= 319.62 \angle -34.8°$ A

Impedance drop in line $= \bar{I}_L \bar{Z} = (262.4 - j182.5)(15 + j75)$

$= (3936 + j19680 - j2738 + 13688)\ \Omega$

$= (17624 + j16942)$ V

(*i*) Sending end line voltage, $\bar{V}_{SL}$:

Sending end phase voltage, $\bar{V}_S = \bar{V}_R + \bar{I}_L \bar{Z}$

$= 63.51 + (17624 + j16942) \times 10^{-3}$ kV

$= 63.51 + (17.62 + j\,16.94) = (81.13 + j\,16.94)$ kV

$= 82.88 \angle 11.8°$ A

$\therefore$ $\bar{V}_{SL} = \sqrt{3} \times 82.88 \angle 11.8° = \mathbf{143.55 \angle 11.8°\ kV.}$ **(Ans.)**

(*ii*) Sending end current $\bar{I}_S$:

$$\bar{I}_{CS} = \frac{1}{2} \bar{Y} \bar{V}_S = \frac{1}{2} j(4.5 \times 10^{-4})(81.13 + j16.94) \times 10^3$$

$= (j18.25 - 3.81)$ A

$$\bar{I}_S = \bar{I}_L + I_{CS} = (262.4 - j182.5) + (j18.25 - 3.81)$$

$= (258.59 - j164.25)$ A $= \mathbf{306.3 \angle -32.4°.}$ **(Ans.)**

(*iii*) Sending end power Factor, $\cos \phi_s$:

$\cos[11.8° - (-32.4°)] = \cos 44.2° = \mathbf{0.717\ (lag).}$ **(Ans.)**

(*iv*) Percentage regulation :

$$V_{RO} = \frac{V_S (-2j/\omega C)}{R + jX - 2j/\omega C} \qquad \text{...Eqn. (14.21)}$$

$$= \frac{82.88\,[-2j/(4.5 \times 10^{-4})]}{15 + j75 - [2j/(4.5 \times 10^{-4})]} = \frac{82.88\,(-j4444.4)}{15 + j75 - j4444.4}$$

$$= \frac{82.88\,(-j4444.4)}{15 - j4369.4} = 84.3\text{ kV}$$

$\therefore$ Percentage regulation $= \dfrac{V_{RO} - V_R}{V_R} \times 100 = \dfrac{84.3 - 63.51}{63.51} \times 100 = \mathbf{32.7\%.}$ **(Ans.)**

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Comparing (*i*) with (*xiv*) and (*ii*) with (*xv*), we get

$$A = D = 1 + \frac{1}{2}\bar{Y}\bar{Z}\ ;\ B = \bar{Z}\ ;\ C = \bar{Y}\left(1 + \frac{1}{4}\bar{Y}\bar{Z}\right) \qquad ...(14.33)$$

Also, $$AD - BC = \left(1 + \frac{1}{2}\bar{Y}\bar{Z}\right)^2 - \bar{Z}\bar{Y}\left(1 + \frac{1}{4}\bar{Y}\bar{Z}\right)$$

$$= 1 + \frac{1}{4}\bar{Y}^2\bar{Z}^2 + \bar{Y}\bar{Z} - \bar{Y}\bar{Z} - \frac{1}{4}\bar{Y}^2\bar{Z}^2 = 1.$$

Example 14.15. *Using nominal -T method find the A, B, C, D parameters of a 3-phase 80 km, 50 Hz transmission line with series inductance of 0.15 + j0.78 ohm per km and a shunt admittance of 5×10^{-6} mho per km.*

Solution. *Given* : Total series impedance, $\bar{Z} = (0.15 + j0.78) \times 80 = (12 + j62.4)\ \Omega$

Total shunt admittance, $\bar{Y} = j5 \times 10^{-6} \times 80 = j(4 \times 10^{-4})$ ℧

For nominal-*T* method, various constants have the following values :

$$\mathbf{A = D} = 1 + \frac{\bar{Y}\bar{Z}}{2} = 1 + \frac{j\,(4 \times 10^{-4})\,(12 + j62.4)}{2}$$

$$= 1 + \frac{j\,0.0048 - 0.02496}{2} = 1 + j\,0.0024 - 0.0125 = \mathbf{0.9875 + j\ 0.0024.} \quad \textbf{(Ans.)}$$

$$\mathbf{B} = \bar{Z}\left(1 + \frac{\bar{Y}\bar{Z}}{4}\right) = (12 + j\,62.4)\left[1 + \frac{j\,(4 \times 10^{-4})\,(12 + j\,62.4)}{4}\right]$$

$$= (12 + j\,62.4)\left(1 + \frac{j\,0.0048 - 0.02496}{4}\right)$$

$$= (12 + j\,62.4)(1 + j\,0.0012 - 0.00624) = (12 + j\,62.4)(0.9938 + j\,0.0012)$$

$$= 11.9256 + j\,0.0144 + j\,62.013 - 0.0749 = \mathbf{(11.851 + j\ 62.027)\ \Omega.} \quad \textbf{(Ans.)}$$

$$C = \bar{Y} = j\,(4 \times 10^{-4}) = \mathbf{j\ 0.0004}\ \text{℧.} \quad \textbf{(Ans.)}$$

Example 14.16. *A 3-phase overhead transmission live delivers a load of 80 MW at 0.8 p.f. lagging and 220 kV between the lines. Its total series impedance per phase and total shunt admittance per phase are 200 ∠80° ohms and 0.0013 ∠90° mho per phase respectively. Using nominal-T method determine the following :*

(*i*) *A, B, C, D constants of the line,* (*ii*) *Sending end voltage,*

(*iii*) *Sending end current,* (*iv*) *Sending end power factor, and*

(*v*) *Transmission efficiency of the line.* **(Agra University)**

Solution. *Given* : Load delivered = 80 MW at 0.8 p.f. lagging

Recieving end phase voltage, $V_R = \dfrac{220}{\sqrt{3}} = 127$ kV

Total series impedance/phase, $\bar{Z} = 200\ \angle 80°\ \Omega$

Total shunt admittance/phase, $\bar{Y} = 0.0013\ \angle 90°$ ℧

(*i*) A, B, C and D constants of the line :

$$\text{Receiving end current} = \frac{80 \times 10^6}{\sqrt{3} \times 220 \times 1000 \times 0.8} = 262.43\ \text{A}$$

$$\cos \phi_R = 0.8, \quad \phi_R = \cos^{-1}(0.8) = 36.87°\ \text{(lag)}$$

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The following points are worth noting :

- The line constants namely resistance, inductive reactance, capacitive susceptance and conductance are *uniformly distributed over the entire line length.*
- The resistance (R) and inductive reactance (X) are the *series elements.*
- The capacitive susceptance (B) and *leakage* conductance (G) are *shunt elements.* G takes into account the energy losses occurring through leakage over insulators or due to corona effect between conductors (Admittance, $Y = \sqrt{G^2 + B^2}$).
- The leakage current through the shunt admittance is maximum at the sending end of the line and decreases continuously as we approach the receiving end of the line, at which point its value becomes zero.

14.7.2. Analysis of Long Transmission Line–Rigorous Method

Fig. 14.22 shows one phase and the neutral return (of zero impedance) of a transmission line. Let dx be the an elemental section of the line at a distance x from the receiving end.

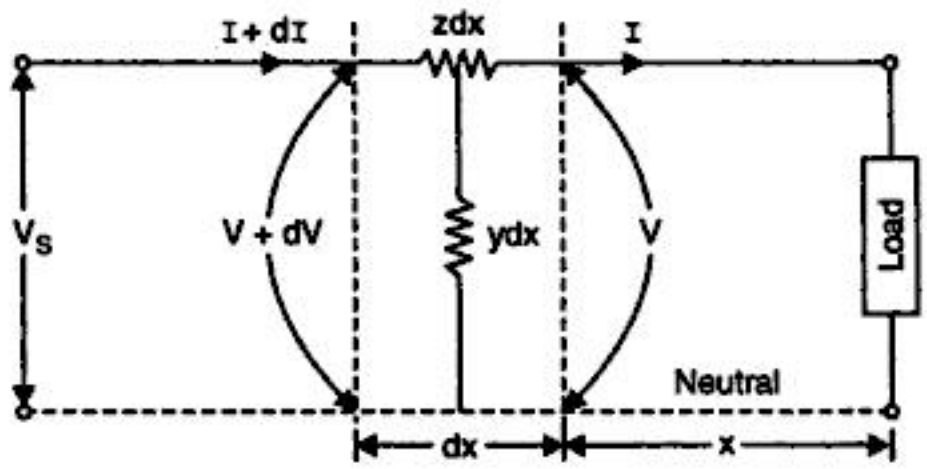

Fig. 14.22. Schematic diagram of a long line.

Let, z = Series impedance of the line per unit length (= $r + jx$, where r and x are respectively resistance and reactance of the line per unit length)

y = Shunt admittance of the line per unit length,

V = Voltage per phase at the end of elements towards receiving end,

$V + dV$ = Voltage per phase at the end of element towards sending end,

$I + dI$ = Current entering the element dx,

I = Current leaving the element dx,

V_S, V_R = Voltages per phase at the sending and receving ends respectively, and

I_S, I_R = Currents per phase at the sending and receiving end respectively,

Then for the small element dx,

zdx = Series impedance, and

ydx = Shunt admittance.

Obviously, the rise in voltage over the element length in direction of increasing x,

$$dV = I\,zdx$$

or,
$$\frac{dV}{dx} = Iz \qquad ...(14.34)$$

Similarly, the difference of current entering the element and that of leaving the element [*i.e.*, $(I + dI) - (I) = dI$],

$$dI = V\,ydx$$

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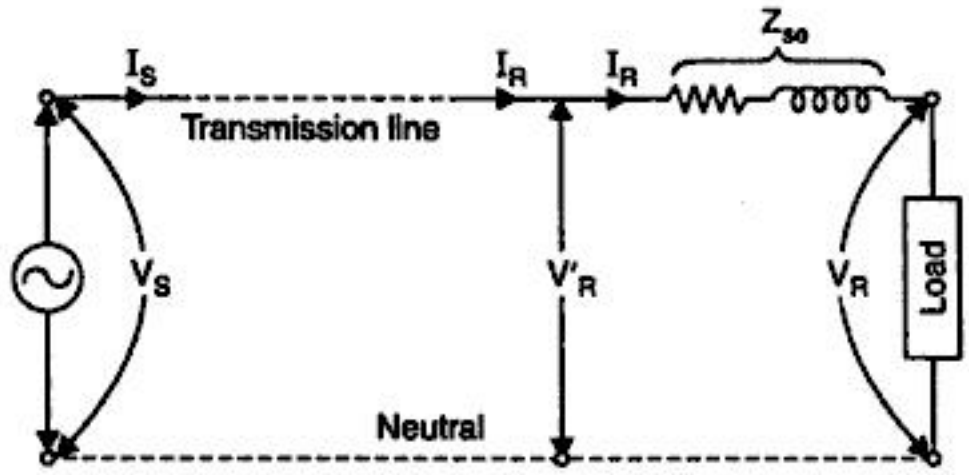

Fig. 14.23. Transmission line with series impedance at the receiving end.

Then, phase voltage at the end of transmission line,

$$\bar{V}'_R = \bar{V}_R + \bar{I}_R \bar{Z}_{se} \qquad ...(i)$$

and,
$$\bar{V}_s = A\bar{V}'_R + B\bar{I}_R = A(\bar{V}_R + \bar{I}_R \bar{Z}_{se}) + B\bar{I}_R$$
$$= A\bar{V}_R + (A\bar{Z}_{se} + B)\bar{I}_R \qquad ...(ii)$$

and,
$$\bar{I}_S = C\bar{V}'_R + D\bar{I}_R$$

Substituting the values of $\bar{V}'_R$ from (i), we get

$$\bar{I}_S = C(\bar{V}_R + \bar{I}_R \bar{Z}_{se}) + D\bar{I}_R = C\bar{V}_R + (C\bar{Z}_{se} + D)\bar{I}_R \qquad ...(iii)$$

Comparing with the general voltage and current equations of the transmission line, we have

$$\left.\begin{aligned} A_0 = A\ ;\ B_0 = A\bar{Z}_{se} + B \\ C_0 = C\ ;\ D_0 = C\bar{Z}_{se} + D \end{aligned}\right\} \qquad ...(14.55)$$

14.7.6. Transmission Line with Series Impedance at the Sending End

Fig. 14.24 shows a transmission line with a series impedance Z_{se} at the sending end. I_S is the sending end current ; this current also passes through Z_{se}. If A, B, C and D are the auxiliary constants of the transmission line, V_R and V_S are the phase voltages at the load and supply end respectively, I_R is the load current and V'_S is the phase voltage at the starting end of the line, then

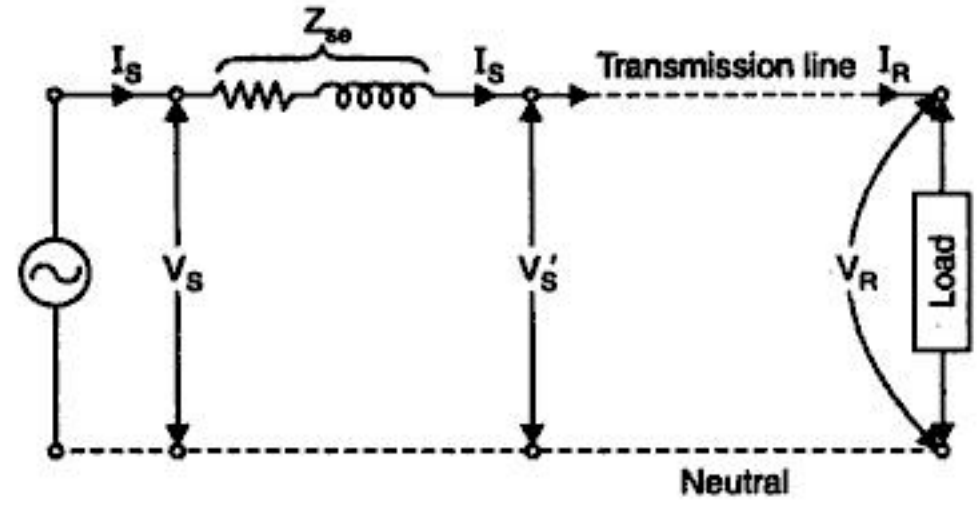

Fig. 14.24. Transmission line with series impedance at the sending end.

$$V'_S = A\bar{V}_R + B\bar{I}_R \qquad ...(i)$$

and,
$$\bar{I}_S = C\bar{V}_R + D\bar{I}_R \qquad ...(ii)$$

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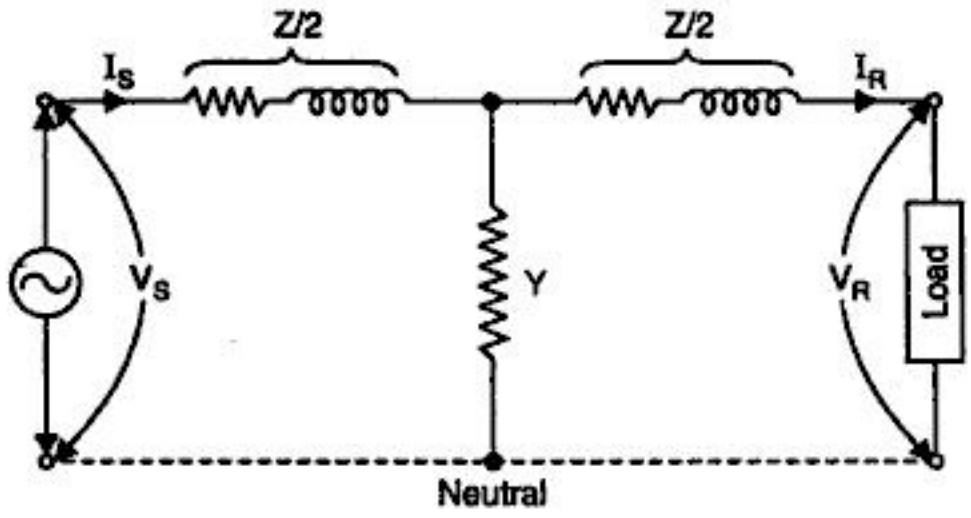

Fig. 14.27. Equivalent T-network of a long transmission line.

$$= \bar{V}_R + \frac{1}{2}\bar{I}_R\bar{Z} + \frac{1}{2}\bar{Z}\left\{\bar{Y}\,\bar{V}_R + \left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{I}_R\right\}$$

$$= \left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{V}_R + \left(\frac{1}{2}\bar{Z} + \frac{1}{2}\bar{Z} + \frac{1}{4}\bar{Y}\,\bar{Z}^2\right)\bar{I}_R$$

$$= \left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{V}_R + \left(\bar{Z} + \frac{1}{4}\bar{Y}\,\bar{Z}^2\right)\bar{I}_R \qquad \ldots(ii)$$

Comparing (*ii*) and (*i*) with general expressions for voltage and current of transmission line, we have

$$\left.\begin{aligned} A = D &= 1 + \frac{1}{2}\bar{Y}\,\bar{Z} && \ldots(iii)\\ B &= \bar{Z} + \frac{1}{4}\bar{Y}\,\bar{Z}^2 && \ldots(iv)\\ C &= \bar{Y} && \ldots(v) \end{aligned}\right\} \qquad \ldots(14.59)$$

From (*iii*) and (*iv*), we get

$$\left.\begin{aligned} \bar{Y} &= C && \ldots(vi)\\ \text{and,}\quad \bar{Z} &= \frac{2(A-1)}{C} && \ldots(vii) \end{aligned}\right\} \qquad \ldots[14.59(a)]$$

14.7.10. Equivalent π-Network of a Long Transmission Line

Sometimes the equivalent π-network of a long transmission line is required to be determined to represent the line accurately by assuming suitable values of lumped constants. Let the transmission line having auxiliary constants A, B, C and D be represented by π-network shown in the Fig. 14.28.

Now, we have

$$\bar{V}_S = \bar{V}_R + \bar{I}\,\bar{Z} = \bar{V}_R + \left(\bar{I}_R + \frac{1}{2}\bar{Y}\,\bar{V}_R\right)\bar{Z} = \left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{V}_R + \bar{I}_R\bar{Z} \qquad \ldots(i)$$

and

$$\bar{I}_S = \bar{I}_R + \frac{1}{2}\bar{Y}\,\bar{V}_R + \frac{1}{2}\bar{Y}\,\bar{V}_S = \bar{I}_R + \frac{1}{2}\bar{Y}\bar{V}_R + \frac{1}{2}\bar{Y}\left\{\left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{V}_R + \bar{I}_R\bar{Z}\right\}$$

$$= \left(\frac{1}{2}\bar{Y} + \frac{1}{2}\bar{Y} + \frac{1}{4}\bar{Y}^2\bar{Z}\right)\bar{V}_R + \left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{I}_R$$

$$= \left(\bar{Y} + \frac{1}{4}\bar{Y}^2\bar{Z}\right)\bar{V}_R + \left(1 + \frac{1}{2}\bar{Y}\,\bar{Z}\right)\bar{I}_R \qquad \ldots(ii)$$

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The circle drawn with receiving end true and reactive power as the horizontal and vertical coordinates is called the "*Receiving end power circle diagram*".

- In order to determine the '*maximum power*' draw a horizontal line from the centre of the circle intersecting vertical axis at the point L and the circle at the point S. Then the distance *LS represents the maximum power for the receiving end.*

(*b*) ***Sending end power circle diagram.*** The circle drawn with sending end true and reactive power as the horizontal and vertical coordinates is known as the *sending end power circle diagram.*

The data required for drawing the sending end power circle diagram is determined [as discussed earlier in (*a*)] as follows :

Substituting, $\bar{I}_S = I_P - jI_Q$,

$\bar{D} = D\angle\delta = D\cos\delta + jD\sin\delta$, and

$\bar{B} = B\angle\beta = B\cos\beta + jB\sin\beta$

in the expression for $\bar{V}_R$, get

$$\bar{V}_R = V_S(D\cos\delta + jD\sin\delta) - (I_P - jI_Q)(B\cos\beta + jB\sin\beta)$$

$$= (V_S D\cos\delta - I_P B\cos\beta - I_Q B\sin\beta) + j(V_S D\sin\delta - I_P B\sin\beta + I_Q B\cos\beta)$$

or, $$V_R^2 = (V_S D\cos\delta - I_P B\cos\beta - I_Q B\sin\beta)^2 + (V_S D\sin\delta - I_P B\sin\beta + I_Q B\cos\beta)^2$$

The above equation is a equation of a circle and can be reduced to the form

$$\left[I_P - \frac{V_S(D\cos\delta \,.\, B\cos\delta + D\sin\delta \,.\, B\sin\beta}{B^2}\right]^2 + \left[I_Q - \frac{V_S(D\cos\delta \,.\, B\cos\beta + D\sin\delta \,.\, B\cos\beta}{B^2}\right]$$

$$= \left(\frac{V_R}{B}\right)^2$$

Multiplying both sides by V_S^2, we get

$$\left[I_P V_S - \frac{V_S^2 D}{B}\cos(\beta - \delta)\right]^2 + \left[I_Q V_S - \frac{V_S^2 D}{B}\sin(\beta - \delta)\right]^2 = \left(\frac{V_S V_R}{B}\right)^2$$

The *co-ordinates of the centre of the circle* and *radius of the circle* given by the above equation are :

$$\left.\begin{aligned} \text{Horizontal } (X) &= \frac{D}{B} V_S^2 \cos(\beta - \delta) \\ \text{Vertical } (Y) &= \frac{D}{B} V_S^2 \sin(\beta - \delta) \end{aligned}\right\} \quad \textit{Co-ordinates of the centre of the circle}$$

$$\textit{Radius} = \frac{V_S V_R}{B}$$

The sending end power circle diagram is shown in Fig. 14.30, $L'S'$ represents the *maximum power for sending end.*

(*c*) ***Universal power circle diagram.*** In receiving end power circle diagram, if V_R is kept constant, the centre of the circles is fixed and if different sending end voltages circles are drawn, these will be concentric ; however if V_R is not constant, these circle will not be concentric. Similarly, if V_S is not constant, the centre of the sending ending power circle diagram will vary. This *limitation is overcome by drawing the 'universal power circle diagram'.*

- In "*universal power circle diagram*" each distance on the original diagram is *divided* by $\frac{V^2}{B}$ where V is the "*reference or base voltage*" and B is the *generalised constant.* This gives *dimensionless units.*

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Solution. *Given :* $V_{RL} = 220$ kV ; $V_{SL} = 240$ kV ; $A = D = 0.99 + j\,0.0132$; $B = (24.75 + j\,165)\,\Omega$; $C = (-\,0.000044 + 0.0011)\,\mho$; Torque angle, $\delta = 30°$.

Active and reactive power :

Line constants : $A = D = 0.99 + j0.0132 = 0.99\,\angle 0.76°$

$B = 24.75 + j165 = 166.85\,\angle 81.47°$

$\therefore$ $A = 0.99$, $\alpha = 0.76°$; $B = 166.85$; $\beta = 81.47°$.

For receiving end power circle diagram :

$$\text{Radius of circle} = \frac{V_{SL}V_{RL}}{B} = \frac{220 \times 240}{166.85} = 316.45 \text{ MVA}$$

Coordinates of the centre of the power circle are :

$$\text{Horizontal coordinate} = \frac{-AV_{RL}^2}{B}\cos(\beta - \alpha)$$

$$= \frac{-0.99 \times (220)^2}{166.85}\cos(81.47° - 0.76°) = -46.36 \text{ MW}$$

$$\text{Vertical coordinate} = \frac{-AV_{RL}^2}{B}\sin(\beta - \alpha)$$

$$= \frac{-0.99 \times (220)^2}{166.85}\sin(81.47° - 0.76°) = -283.4 \text{ MVAR}$$

Using scale : 1 cm = 40 MW (horizontally),

1 cm = 40 MVAR (vertically) ;

$$\text{Radius of the circle} = \frac{316.45}{40} = 7.9 \text{ cm},$$

$$\text{Horizontal coordinate} = -\frac{46.36}{40} = -1.16 \text{ cm, and}$$

$$\text{Vertical coordinate} = -\frac{283.4}{40} = -7.1 \text{ cm.}$$

Draw the circle diagram as shown in Fig. 14.36.

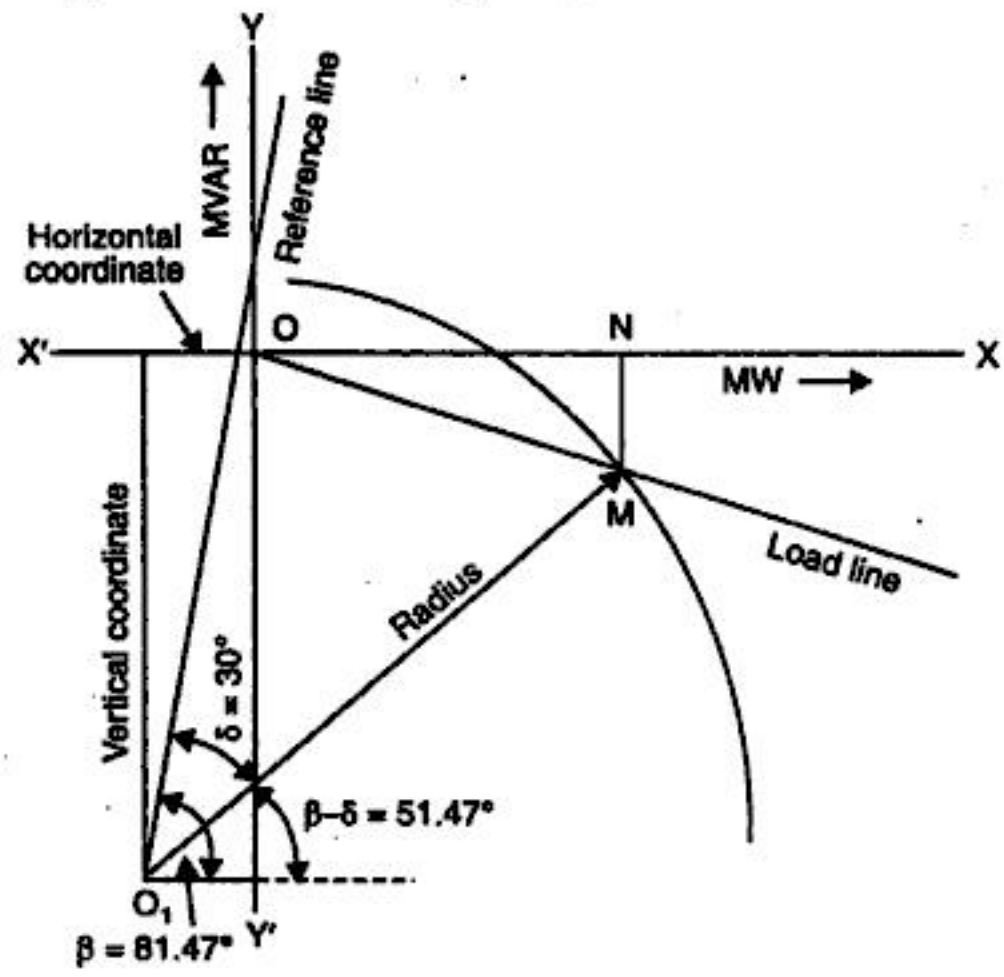

Fig. 14.36

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Using scale : 1 cm = 0.2 p.u. true power (Horizontally)
1 cm = 0.2 p.u. reactive power (Vertically)

- Locate point O_R having coordinates $\left(\frac{0.651}{0.2} \text{ and } \frac{1.61}{0.2}\right)$ *i.e.*, (3.26 cm, 8.05 cm) and from point O_R draw load line at an angle $\cos^{-1}(0.8)$ *i.e.*, 36.87° inclined to the horizontal and an horizontal line $O_R N$ of magnitude 0.2144 *i.e.*, (1.072 cm).
- Draw a line NM perpendicular from the point N cutting the load line at the point M, O_1M is the radius of the universal power circle (Fig. 14.41)

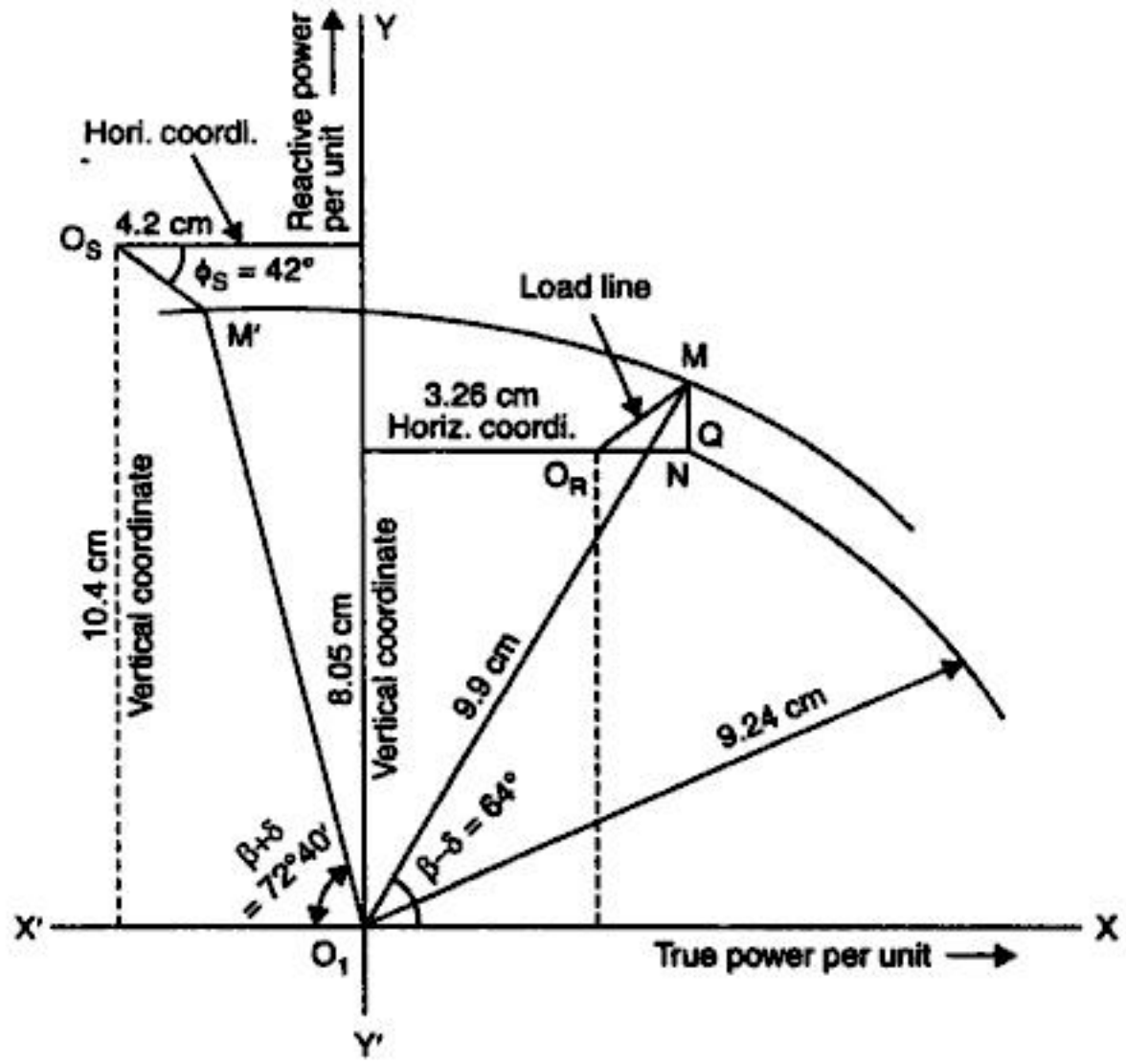

Fig. 14.41

From circle diagram $O_1M = 9.9$ cm ...(By measurement)

$= 9.9 \times 0.2 = 1.98$ p.u.

$\therefore \quad O_1M = \frac{V_{RL}V_{SL}}{V^2}$ p.u.

$\therefore \quad V_{SL} = \frac{O_1M \times V^2}{V_{RL}} = \frac{1.98 \times 100^2}{132} = 150$ kV. (Ans.)

$\beta - \delta = 64°$ ...(By measurement)

$\therefore \quad \delta = \beta - 64° = 68°\,20' - 64° = 4°\,20'$

and, $\beta + \delta = 68°\,20' + 4°\,20' = 72°\,40'$

The coordinates of point O_S (the point of sending end power measurement) with respect of the origin (the centre of universal power circle) are :

Horizontal coordinate $= -D\frac{V_{SL}^2}{V^2}\cos(\beta - \alpha)$

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7. A 3-phase, 50 Hz, 100 km long transmission line has the following line constants :
Resistance/phase/km = 0.1 Ω ; Reactance/phase/km = 0.5 Ω ; Susceptance/phase/km = 10×10^{-6} mho.
If the line supplies load of 20 MW at 0.9 p.f. lagging at 66 kV at the receiving end, determine the following :
(*i*) Sending end power factor,
(*ii*) Percentage regulation, and
(*iii*) Transmission efficiency.
Use nominal-π method [**Ans.** (*i*) 0.905 lag ; (*ii*) 15.27% ; (*iii*) 94%]

8. A 3-phase, 50 Hz, overhead transmission line, 100 km long has 110 kV between lines at the receiving end and has the following constants :
Resistance/km/phase = 0.153 Ω ; Inductance/km/phase = 1.21/mH ; Capacitance/km/phase = 0.00958 μF.
The line supplies a load of 20 MW at 0.9 p.f. lagging. Calculate, using nominal-π representation, the following :
(*i*) Sending end line voltage, (*ii*) Sending end current,
(*iii*) Sending end power factor, (*iv*) Percentage regulation, and
(*v*) Transmission efficiency of the line. [**Ans.** (*i*) 115.645 kV, (*ii*) 109 A ; (*iii*) 0.9423 (lag.) (*iv*) 5.13% ; (*v*) 97.21%]

9. A balanced 3-phase load of 30 MW is supplied at 132 kV, 50 Hz and 0.85 p.f. lagging by means of a transmission line. The series impedance of a single conductor is (20 + *j*52) ohms and the total phase-neutral admittance is 315×10^{-6} mho. Using nominal-*T* method determines.
(*i*) *A, B, C, D* constants, (*ii*) Sending ending line voltage, and
(*iii*) Regulation of the line. [**Ans.** (*i*) $A = D = 0.992 \angle 0.18°$, $C = 0.000315 \angle 90°$, (*ii*) 143 kV, (*iii*) 9.26%]

10. A 132 kV, 50 Hz, 3-phase transmission lines delivers a load of 50 MW at 0.8 p.f. lagging at the receiving end and has the following constants :
$A = D = 0.95 \angle 1.4°$; $B = 96 \angle 78°$; $C = 0.0015 \angle 90°$. Determine the following :
(*i*) Percentage regulation of the line, and
(*ii*) Charging current ; Use nominal-*T* method. [**Ans.** (*i*) 30% ; (*ii*) 128.2 ∠93.1°A]

11. The constants for a 132 kV line are as under :
$A = D = 0.98 \angle 3°$; $B = 110 \angle 75°$ Ω ; $C = 0.0034 \angle 80°$ ℧.
The load at the receiving end is 40 MVA at 132 kV and power factor 0.8 lagging. Draw the circle diagram and find out the following :
(*i*) Sending end voltage.
(*ii*) Leading MVAR for this load at the receiving end, if the sending end voltage is 440 kV.
(Panjab University)
[**Ans.** (*i*) 157.8 kV ; (*ii*) 23 MVAR]

12. A 3-phase overhead line has resistance and reactance per phase of 25 Ω and 90 Ω respectively. The supply voltage is 145 kV while the load-end voltage is maintained at 132 kV for all loads by an automatically controlled synchronous phase modifier. If the kVAR of the modifier has the same value for zero load as for a load of 50 MW, find the rating of the modifier and the power-factor of the load. **(U.P.S.C)**
[**Ans.** 19 MVAR ; 0.95 lag]

13. A single-circuit, 50 Hz transmission line is 500 km long and has the following *ABCD* constants :
$A = D = 0.895 \angle 1.5°$; $B = 182.5 \angle 78.5°$; $C = 0.00111 \angle 90.5°$ ℧.
Construct a universal power circle diagram and from the diagram determine :
(*i*) The sending end voltage for a load of 80 MVA at 215 kV and 0.8 p.f. lagging at the receiving end.
(*ii*) The voltage regulation for the loading as in (*i*), and
(*iii*) The reactive power supplied by the line and by a synchronous phase modifier in parallel with the load, when the loading is 80 MVA at 215 kV and 0.9 p.f. lagging. Given that the sending end voltage is 236 kV. Also determine the power factor at the receiving end of the line. **(Agra University)**
[**Ans.** (*i*) 263 kV ; (*ii*) 22.33 % ; (*iii*) 24.45 MVAR/line) ; 14.3 MVAR lead ; 0.956 lagging]

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Disadvantages :

1. High maintenance cost.
2. Location of fault is difficult.
3. Load extension necessitates completely new excavation costing as much as the original work.
4. The alteration in the cable network cannot be made easily.
5. The cable sheath may sometimes undergo chemical changes and get damaged due to impurities present in the soil.
6. This method cannot be used in congested areas where excavation is expensive and inconvenient.

2. Draw-in system. This method of cable laying is *suitable for congested areas where excavation is expensive and inconvenient.*

It is *most suitable for short length cable routes* such as in workshops railway bridge crossing, road crossing where frequent digging is costlier or impossible.

- In this method a line of conduits, ducts or tubes made of either iron, glazed stoneware, clay or cement concrete are laid in ground with manholes at suitable positions along the cable route. The cables are then pulled into position.
- Separate pipes and ducts (or multiple way ducts) are provided for each cable laid in the same duct.
- Care must be taken that where the duct line changes direction ; depths, dips and offsets be made with very long radius so that a large cable may be pulled easily between the manholes. The distance between the manholes should not be too long so as to simplify the pulling in of the cables.
- The cables to be laid in this way need *not be armoured but must be provided with serving of hessian and jute in order to protect them when being pulled into the ducts.*

Fig. 16.9 shows section through 4-way underground duct line. Three of the ducts carry transmission cables and the fourth duct carries relay protection connection, pilot wires.

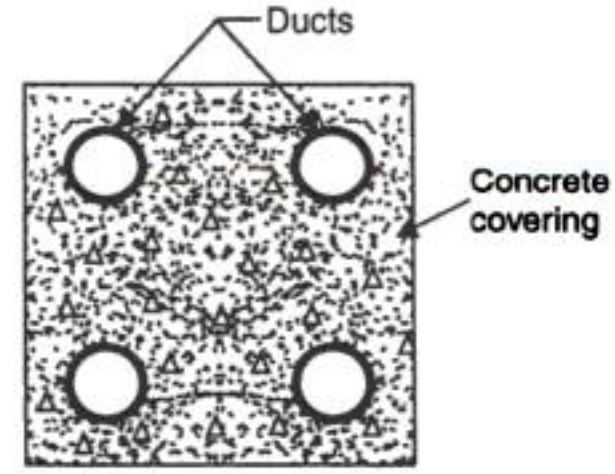

Fig. 16.9. Draw in system.

Advantages :

1. *Less chances of occurrence of fault* (owing to strong mechanical protection provided by the system).
2. It is *easy to carry out repairs, alterations or additions* to the cable network without opening the ground.
3. Since the cables are not armoured, therefore, joints become simpler and *maintenance cost is reduced considerably.*

Disadvantages :

1. *Very high initial cost.*
2. Owing to the close grouping of cables and unfavourable conditions for dissipation of heat the *current carrying capacity of the cables is reduced.*

3. Solid system :

- In this method the cable is laid in open pipes or troughs dug out in earth along the cable route. The troughing is of cast iron, stoneware, asphalt or treated wood. After laying the cable in position, the troughing is filled with a bituminous or asphaltic compound and covered over.

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the ratio of the other two arms of the testing network at balance is 4 : 1, find the distance of the fault from the testing end of cable.

Solution. *Given* : Loop length = 2 × 400 = 800 m ; $\frac{P}{Q} = 4$

$$\frac{P}{Q} = \frac{4}{1} \qquad \text{or} \qquad \frac{P+Q}{Q} = \frac{4+1}{1} = 5$$

Distance of fault from test end,

$$D = \frac{Q}{P+Q} \times \text{loop length}$$

$$= \frac{1}{5} \times 800 = \mathbf{160\ m.} \quad \textbf{(Ans.)}$$

Example 16.21. *In a Murray loop test for a fault to earth on a 400 m length of cable having a resistance of 1.5 Ω/km, the faulty cable is looped with a sound cable of the same length but having a resistance of 3.5 Ω/km. The resistances of the other two arms of the testing network at balance are in the ratio 3 : 1. Calculate the distance of the fault from the testing end of the cable.*

Soluton. $\frac{P}{Q} = \frac{3}{1}$, or, $\frac{P+Q}{Q} = \frac{3+1}{1} = 4$

$$\text{Loop resistance} = \frac{1.5}{1000} \times 400 + \frac{3.5}{1000} \times 400 = 2\ \Omega$$

Resistance of the faulty cable from the test end upto fault point,

$$X = \frac{Q}{P+Q} \times \text{loop resistance} = \frac{1}{4} \times 2 = 0.5\ \Omega$$

Distance of fault point from the testing end,

$$d = \frac{X}{15/1000} = \frac{0.5}{15/1000} = \mathbf{333.33\ m.} \quad \textbf{(Ans.)}$$

Example 16.22. *Varley loop test is conducted to locate an earth fault on a 25 km long cable. The resistance per km of single conductor is 15 Ω. The loop is completed with a similar sound conductor. At balance, the variable resistance connected to the faulty conductor is 150 Ω. The fixed resistors have equal values. Calculate the distance of the fault from the test end.*

Solution. Resistance of faulty cable from test end to fault point,

$$X = \frac{Q(R+X) - PS}{P+Q}$$

Here, $P = Q\ ;\ S = 150\ \Omega\ ;\ R + X = 25(15 + 15) = 750\ \Omega$

$\therefore$ $$X = \frac{Q(750) - Q \times 150}{Q+Q} = 300\ \Omega$$

The resistance per km = 15 Ω

$\therefore$ Distance of fault from the test end,

$$d = \frac{X}{15} = \frac{300}{15} = \mathbf{20\ km.} \quad \textbf{(Ans.)}$$

16.15. CAUSES OF FAILURE OF UNDERGROUND CABLES

The following are the (probable) *causes of failure of underground cables* :

1. Mechanical puncturing of the lead sheathing of a cable (during excavation and building operations).

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17.2. CLASSIFICATION OF STABILITY CONDITIONS

For the purpose of analysis the stability conditions may be classified as follows :

1. Steady state stability.
2. Transient stability.
3. Dynamic stability.

1. Steady state stability :

The ***"steady state stability"*** *is the stability of the system under conditions of gradual or relatively slow change in load.* The load is assumed to be applied at a rate which is slow when compared either with the natural frequency of oscillations of the major parts of the system or with the rate of change of field flux in the rotating machine in response to the change in loading.

- The study of steady state stability is basically concerned with the determination of the upper limit of machine loadings before losing synchronism, provided the loading is gradually increased.
- In case of interconnected systems, synchronism between the ends may be lost once the magnitude of power flow exceeds the steady state stability limit.

2. Transient stability :

"Transient stability" *refers to the maximum flow of power possible through a point without losing the stability with sudden and large changes in the network conditions such as brought about by faults, by sudden large increment of loads.*

Transient stability of a power transmission system is its *inherent ability to recover* normal operation following sudden and/or severe disturbance (*e.g.* the fault).

Transient stability is *characterised by* the highest magnitude of power flow just prior to the transient disturbance for which the system can remain in synchronism once the transient fault is withdrawn or cleared.

- The *transient stability limit* is almost always *lower than the steady state limit*, but unlike the latter, it may exhibit different values depending on the nature, location and magnitude of disturbance.

3. Dynamic stability :

"Dynamic stability" is *the ability of a power system to remain in synchronism after the 'initial swing' (transient stability period) until the system has settled down to the new steady-state equilibrium condition.*

The system is said to be dynamically stable if the oscillations do not acquire more than certain amplitude and die out quickly (*i.e.*, the system is well damped). In a dynamically unstable system, the oscillation amplitude is large and these persist for a long time (*i.e.*, the system is underdamped). This kind of instability behaviour constitutes a serious threat to system security and creates very difficult operating conditions.

Dynamic instability is *more probable than steady state instability.*

Dynamic stability can be significantly improved through the use of power system stabilizers.

- *Computer simulation* is the only effective means of studying dynamic stability problems. The same simulation programmes are, of course, applicable to transient stability studies as well.

Note. In addition to power flow stability, voltage stability is also a major criterion for successful A.C. power transmission. *'Voltage instability'* is characterised by a state of power system when the load end voltage drops abnormally causing withdrawal of high currents from the source even though the power flow starts ceasing and the power angle between the two bus voltages way exceed their rated value for stable power transfer.

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For *any value of* δ *the difference in power developed between generator and motor is equal to 'line losses'*. When the line resistance and shunt admittance are negligible, then the power transferred between generator and the motor,

$$P = P_M = P_G = \frac{V_G V_M}{X} \sin \delta \qquad ...(v)$$

when $\delta = 90°$, the power transferred will be maximum,

i.e.
$$P_{max} = \frac{V_G V_M}{X} \qquad ...(vi)$$

From the above eqn. it is evident that the *maximum power that can be transferred between a generator / alternator* and a motor is *directly proportional to the products of internal e.m.fs of the two machines and inversely proportional to reactance of the line.*

Methods of improving steady state stability :

In practice the following methods are used to improve steady state stability :

1. Higher excitation voltages.

2. Reducing the impedance between the stations (By adding machines or lines in parallel or by using machines of lower inherent impedance).

3. The optimum conditions of $X = \sqrt{3}R$ for maximum power transfer is approached by the use of series capacitors for overhead lines and series reactors for underground cables.

4. Quick response excitation system.

Example 17.1. *Deduce an expression for the maximum steady state power which can be transmitted over a line (neglecting capacitance of the line) if the voltage at each end is kept constant.*

Show that if the reactance X of the line be varied the resistance R remaining constant the maximum steady state power that could be transmitted over the line would be greatest when $X = \sqrt{3}R$.

Sol. Refer Fig. 17.3.

Let, V_S = Sending end voltage,

V_R = Receiving end voltage,

$I_S = I_R = I$ = Sending end and receiving end currents (same, since capacitance is neglected)

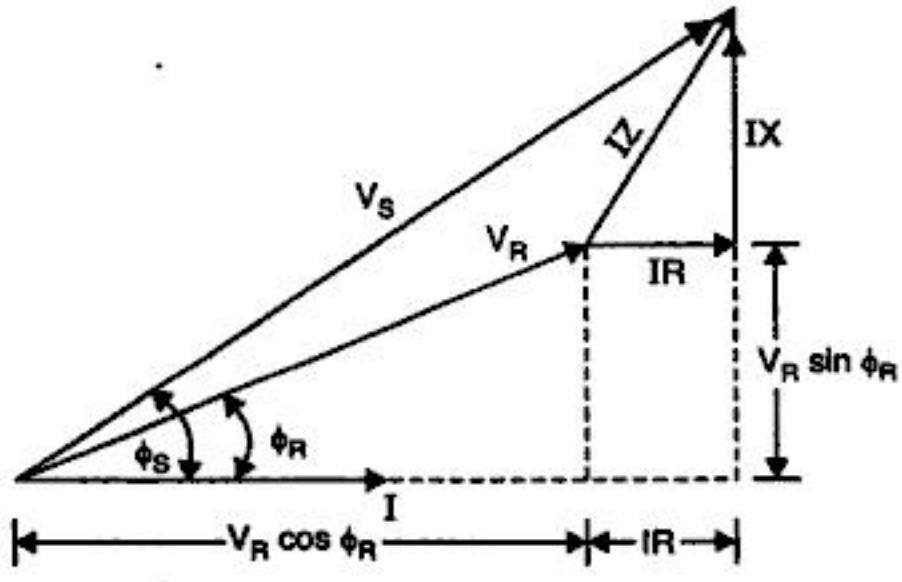

Fig. 17.3. Phasor diagram.

IR, IX = Component voltage drops due to the impedance Z of the line, when current I flows through it. From the phasor diagram, we have

$$V_S \cos \phi_S = V_R \cos \phi_R + IR \qquad ...(i)$$

$$V_S \sin \phi_S = V_R \sin \phi_R + IX \qquad ...(ii)$$

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Applications of equal area criterion *include the following :*

1. *Effects of increase in load.*
2. *Effects of switching operations.*
3. *Effects of faults with subsequent circuit isolation.*

1. Effects of increase in load. From the point of view of transient disturbance and system stability the following are the *two* possibilities of increasing the load :

(*i*) The total load *exceeds* the steady state limit of the system.

(*ii*) The rate of increase in load is so high as to set up *oscillations which cross the critical point.*

Let us consider a synchronous motor connected to an infinite bus-bar and operating at synchronous speed with mechanical output P_0. Let δ_0 (determined from the power-angle diagram shown in Fig. 17.6) be the load angle corresponding to P_0.

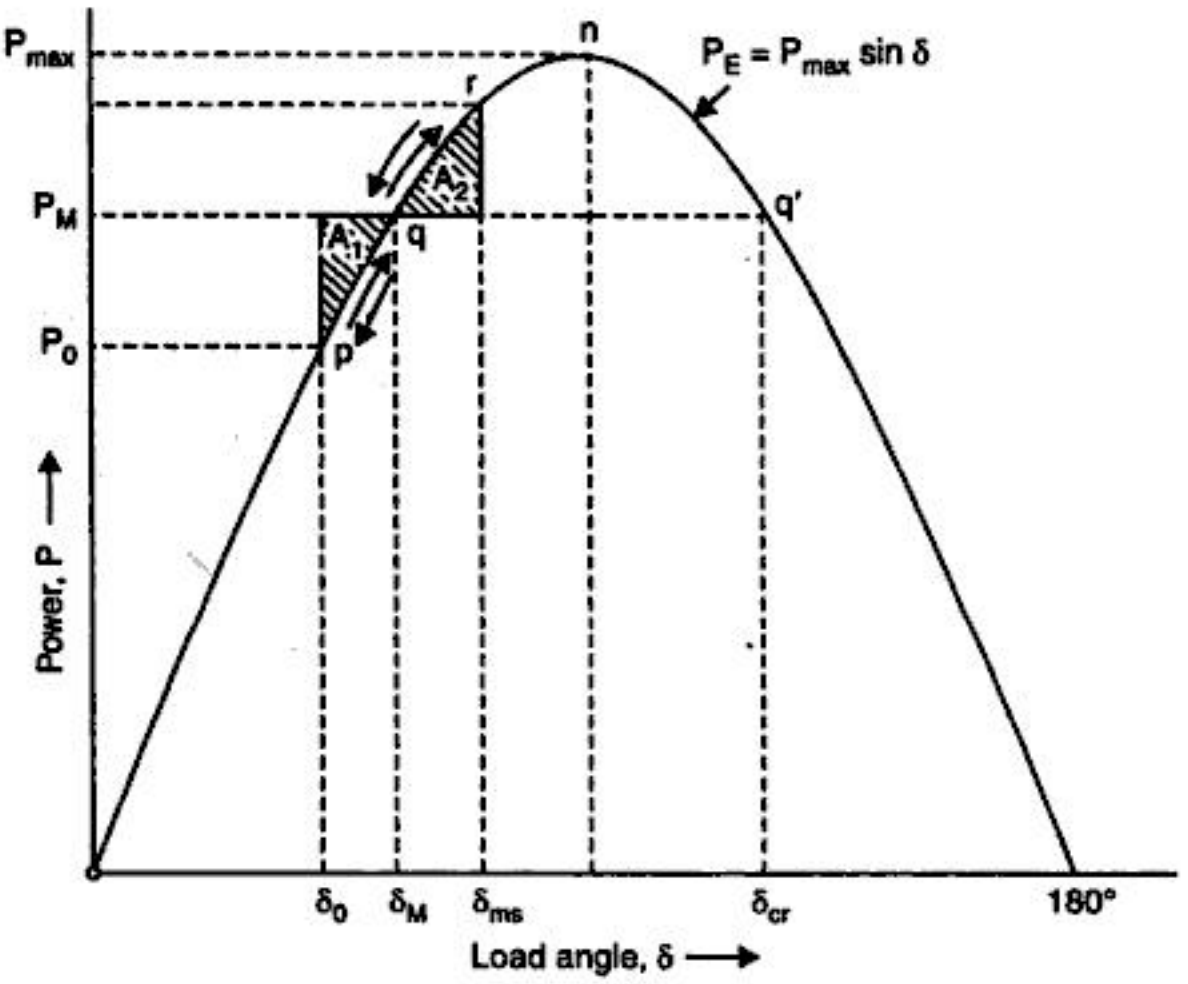

Fig. 17.6. Sudden change of load–equal area criterion.

The power-angle diagram is drawn by using the relation,

$$P_E = \frac{V_G \cdot V_M}{X} \sin \delta$$, neglecting the system (motor, transmission line, transformers etc.)

where, V_G = Voltage of the infinite bus-bars,

V_M = Voltage behind the transient reactance of the synchronous motor,

X = Transient reactance of the system, and

δ = Load or torque angle.

Under these conditions,

$$P_0 = P_E = \frac{V_G \cdot V_M}{X} \sin \delta$$

where, P_0 = Mechanical power output, and

P_E = Electrical input.

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$$\therefore \qquad \cos \delta_{cl} = \frac{(\delta_m - \delta_0) \sin \delta_0 - \gamma_1 \cos \delta_0 + \gamma_2 \cos \delta_m}{\gamma_2 - \gamma_1} \qquad ...(17.39)$$

Now from the curves,

$$P_M = P_{max} \sin \delta_0 = \gamma_2 P_{max} \sin \delta_m = \gamma_2 P_{max} \sin (\pi - \delta_m)$$

or, $$\sin \delta_0 = \gamma_2 \sin (\pi - \delta_m)$$

or, $$\delta_m = \pi - \sin^{-1}\left(\frac{\sin \delta_0}{\gamma_2}\right) \qquad ...(17.40)$$

Thus if γ_1, γ_2 and δ_0 are known, the critical clearing angle δ_{cl} can be obtained.

17.4.5. Transient Stability in a Multi-machine System

In order to determine the multi-machine stability the following *steps* can be taken :

1. Determine the voltage behind transient reactance for all the generators from the pre fault load data ; this voltage is kept constant. The angle with this voltage is the initial rotor angle.

2. Record the prime mover output P_M (= P_E in steady state).

3. Augment the load flow network by the generator transient reactances. Assume the network buses to be behind the transient reactances.

4. Determine $(Y)_{Bus}$ during fault, and post fault clearing condition.

5. Obtain the generator outputs (using $P - \delta$ equation) during the fault condition.

6. Solve the swing equation. Obtain δ vs t which predicts stability.

7. Repeat steps 5 and 6 for post fault clearing mode.

17.4.6. Transient Stability Improvement

The transient stability can be improved by the following methods :

1. By using machines of higher inertia or by connecting the synchronous motors to heavy flywheels.

2. By increasing the system voltage.

3. By reducing the transfer reactance.

4. By using high neutral grounding impedance.

5. By reducing the severity of faults which can be achieved by using lightning arrestors for protection of lines.

6. By the use of high speed circuit breakers.

- To improve transient stability the governors attached to the turbines driving alternators should be high speed one so as to adjust the generator input quickly as per demand of the load.
- Voltage regulators employed on the lines should be quick acting ones.

Example 17.4. *A 3-phase line has a reactance of 11 Ω per phase. The voltage at each end is maintained at 132 kV (line-to-line). Determine :*

(i) The maximum steady state power that can be transmitted by the line.

(ii) The limits of angular oscillations for transient stability, when the above line develops a sudden jerk at $\frac{2}{5}$*th of the steady state limit.*

Sol. *Given :* $X = 11\ \Omega$, $V_{SL} = V_{RL} = V_L = 132$ kV

(i) Maximum steady state power :

Maximum steady state power that can be transmitted by the line for all the three phases,

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18

Control of Reactive Power, Voltage and Load Frequency in Transmission Systems

18.1. Generation and absorption of reactive power. 18.2. Effect of reactive power on voltage and voltage regulation. 18.3. Relations between δQ, δP and V at a node. 18.4. Reactive compensation in power system. 18.5. Types of compensators. 18.6. Methods of voltage control in transmission system. 18.7. Relations between voltage and reactive power, frequency and active power. 18.8. Control of load frequency. Highlights—Theoretical Questions.

18.1. GENERATION AND ABSORPTION OF REACTIVE POWER

The study of generation and absorption of reactive power in the power system is essential since the reactive power is very precious in keeping the voltage of the power system stable. *Whereas frequency is the indicator of active power balance, voltage is the sole indicator of reactive power balance.*

The components responsible for the generation and absorption of reactive power in the power system are :

1. Alternators.
2. Overhead lines and transformers.

1. Alternators :

- An *overexcited alternator generates reactive power while an underexcited machine absorbs it.* Normally the alternators are run in overexcited mode such that they can act as main source of reactive power supply to the power system.
- The reactive power supply capability is determined by the short circuit ratio.

2. Overhead lines and transformers :

- *A fully loaded **overhead line*** absorbs reactive power, given by I^2X, where I and X are the line current and line reactance (Ω) per phase respectively. The distributed shunt capacitances throughout the line, on light loads or at no load, become predominant and consequently the line supplies charging VAR*i.e.* generates reactive power (given by $2\pi fCV^2$, where V is the line voltage, f the system frequency and C the line-to-earth capacitances).
  — ***Cables** generate reactive power* due to the various cable capacitances.
- ***Transformers** always absorb reactive power*, given by :

$$\frac{I^2VX_t}{I_{rated}} \ VAR/\text{phase}$$

where, I = Phase current,

I_{rated} = Rated phase current,

V = Phase voltage, and

X_t = The p.u. reactance of the transformer.

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HIGHLIGHTS

1. Whereas frequency is the indicator of active power balance, voltage is the sole indicator of reactive power balance.
2. *Alternators* and *overhead lines and transformers* are the components which are responsible for the generation and absorption of reactive power.
3. The various types of compensators are : (*i*) Shunt capacitors ; (*ii*) Synchronous compensator ; (*iii*) Series capacitors.
4. The methods of voltage control in a transmission system are :
   (*i*) Transformer tap changing ; (*ii*) Booster or regulating transformer ;
   (*iii*) Static VAR system.

THEORETICAL QUESTIONS

1. Name the components of power system which generate or absorb power.
2. Define the relationship between the incremental changes of P, Q and V in a load node.
3. What is reactive compensation ? What are its advantages ?
4. Enumerate various types of compensators and explain any one of them.
5. What is a booster transformer ? Where is it used ?
6. Explain briefly the various methods of voltage control in a transmission system.
7. Explain briefly 'load frequency control'.

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be generated at comparatively low voltages by units of relatively low power ratings. As yet there is no economical method of raising the D.C. voltage for transmission and lowering it for distribution.

For certain applications, *D.C. supply is absolutely necessary* ; *e.g.*, D.C. supply is required for the *operation of variable speed machinery such as D.C. motors, electro-chemical work and electric traction.*

In a D.C. system the electrical energy may be fed and distributed either by two-wire or by three-wire system.

Two-wire D.C. distribution systems. Fig. 19.2 shows a two-wire D.C. distribution system from generating station or substation to the consumer's terminals.

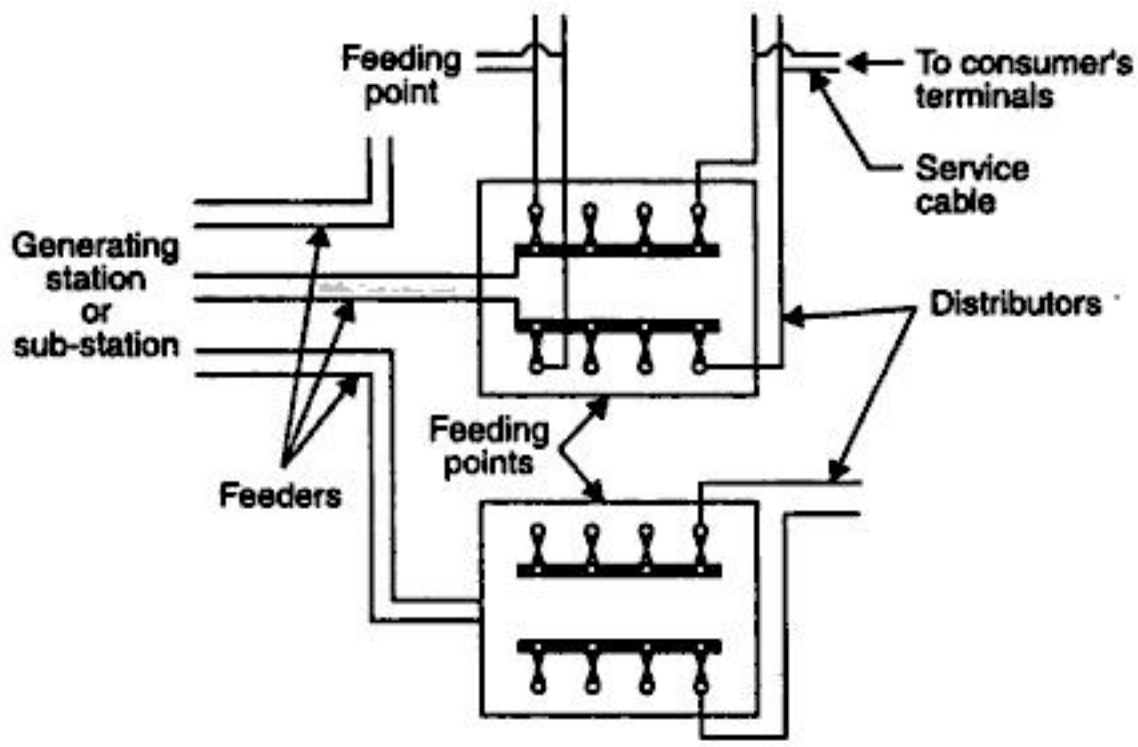

Fig. 19.2. Two-wire D.C. system.

- This system consists of two wires, one outgoing (known as *positive wire*) and another returning one (*negative wire*).
- Untapped feeders run into bus-bars in suitable feeding points in the distribution area.
- Distribution cables are connected to the bus-bars through fuses or links.
- Each separate consumer is fed from the distributor by a service cable tapped on to the distributor at the nearest convenient point.
- The electrical appliances and motors etc. are connected in parallel between the two wires.

Three-wire D.C. distribution systems :

- This system consists of *two outers* and an *earthed middle wire* known as *neutral wire.*
- The lamps or consumer apparatus are connected between the neutral and one of the outers.
- The voltage between the outers being twice that of consumer's terminals *increases the transmission efficiency and reduces the copper cost.*

19.2.1. Types of Distributors

The distributors are of the following *types* :

1. Distributors fed at one end.
2. Distributors fed at both ends.
3. Distributors fed at the centre.
4. Ring distributor.

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Out-of-balance current = 2000 – 1600 = 400 A

Current through B_1 = (2000 + 600) – 2432 = **168 A. (Ans.)**

Current through B_2 = 400 – 168 = **232 A. (Ans.)**

Example 19.29. *A D.C. 3-wire system with 500 V across outers supplies 1000 A on +ve side, 800 A on –ve side and 1000 A across outers. The rotary balancer has an armature resistance of 0.1 Ω and takes 10 A on no load. Calculate :*

(i) Current loading of each balancer unit,

(ii) Voltage across each balancer, and

(iii) Load on the main generator. **(Panjab University)**

Sol. *Given :* Voltage across outers = 500 V

Current supplied on +ve side = 1000 A

Current supplied on –ve side = 800 A

Current supplied across outers = 1000 A

Armature resistance, R_a = 0.1 Ω

No-load current of the balancer = 10 A

Total current on +ve outer = 1000 + 1000 = 2000 A

Total current on –ve outer = 800 + 1000 = 1800 A

Current in the middle wire, I_N = 2000 – 1800 = 200 A.

Since the load on +ve side is more, therefore, machine B_1 will run as a *generator* and machine B_2 will run as a *motor.*

(i) Current loading of each balance unit :

Refer to Fig. 19.60. Let the current loading of B_1 and B_2 be I_{B1} and I_{B2} respectively.

Since current in the neutral, $I_N = I_{B1} + I_{B2}$

$$\therefore \quad I_{B1} = I_N - I_{B2} = 200 - I_{B2}$$

Let V_{B1} and V_{B2} be the voltages across machines B_1 and B_2 respectively.

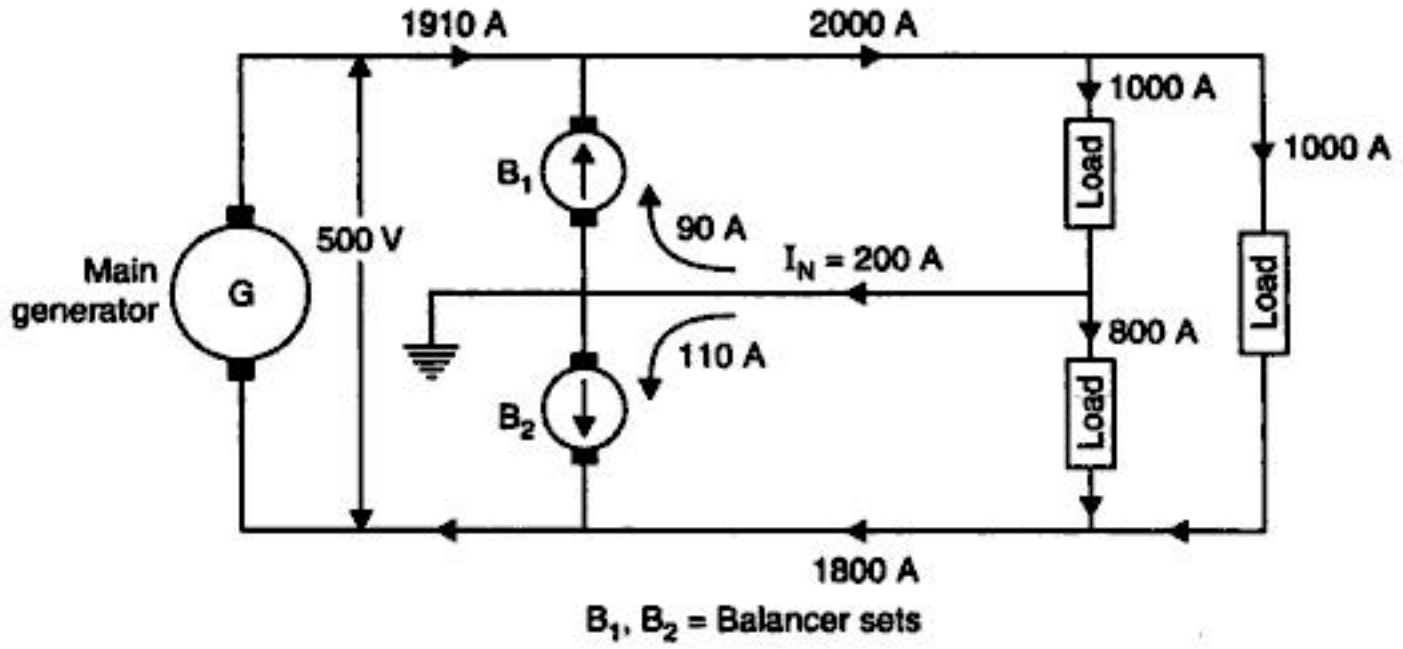

Fig. 19.60

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Factories : Fig. 19.66 showing how supply comes to *factories.*

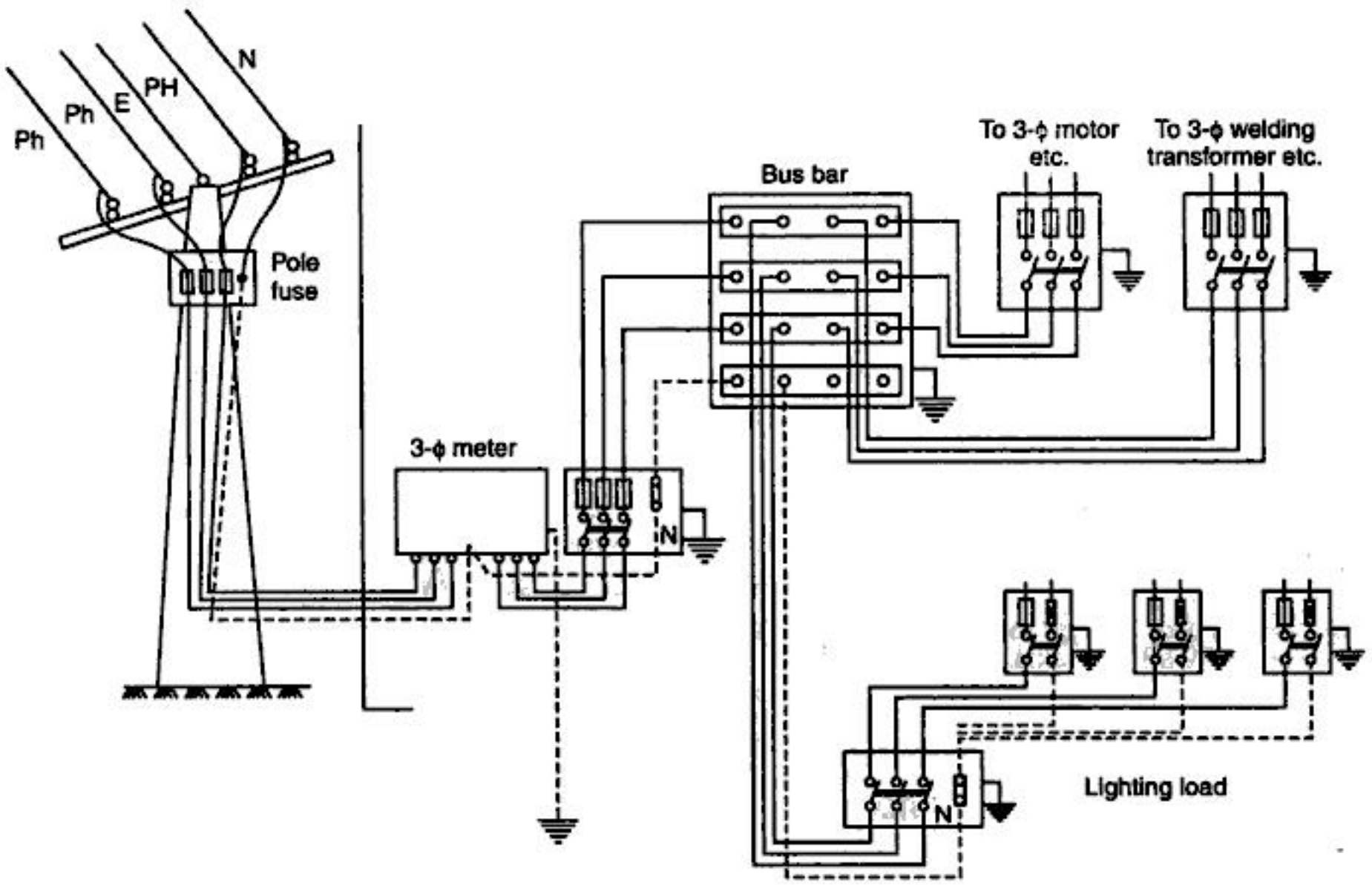

Fig. 19.66. Factory wiring.

- In factories or big buildings 3-phase four-wire supply comes through overhead lines or cables to the factory in 3-phase meters, supplied by supply company.
- From there, as shown in Fig. 19.66 supply comes in ICTP switch from which supply enters in bus-bar section. From there it is distributed to different sections through ICTP switches to give supply to 3 phase motors etc. and ICDP for single phase to give supply to lighting load.

19.3.2. A.C. Distribution Calculations

A.C. distribution calculations differ from the D.C. distribution in the following *respects* :

1. In D.C. system, the voltage drop is due to resistance alone but in A.C. system the voltage drops are due to the *combined effects of resistances, inductances and capacitances.*

2. In D.C. system, all additions and subtractions of currents are simply mathematical but in A.C. system all additions and subtractions will be *vectorially* and therefore, currents and voltages will be expressed in *symbolic notations.*

3. At the load point the phase angle between voltage and current plays an important part. Loads tapped off from the distributor are generally at different power factors. There are two ways of referring power factor : (*i*) It may be *referred to supply or receiving end voltage which is reference vector ;* (*ii*) It may be *referred to the voltage at the load point itself.*

4. All methods employed for solution of D.C. distributors and networks shall hold good in solution of A.C. distributors and networks, the only difference is that all impedances, currents and voltages shall be expressed vectorially (*i.e.*, symbolically) with current or voltage as reference vector.

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Taking voltage at far end D, V_D as the reference vector,

$$V_D = (220 + j0)\ \text{V}$$

Current in section CD, $\bar{I}_3 = 50(0.88 - j0.475) = (44 - j23.75)$

Voltage at load point C, $\bar{V}_C = \bar{V}_D + \bar{I}_3 \bar{Z}_{CD}$

$$= (220 + j0) + (44 - j23.75)(0.036 + j0.06)$$

$$= (220 + j0) + (3.009 + j1.785) = (223.009 + j1.785)\ \text{V}$$

Phase angle between V_C and V_D,

$$\theta_1 = \tan^{-1}\left(\frac{1.785}{223.009}\right) = 0.46°$$

The load current I_2 lags behind V_C by an angle

$$= \cos^{-1} 0.85 = 31.79°$$

The load current I_2 *lags* behind voltage at far end V_D by an angle $(31.79° - 0.46°) = 31.33°$

Load current at point C, $\bar{I}_2 = 40(\cos 31.33° - j \sin 31.33°)$

$$= 40(0.854 - j0.52) = (34.16 - j20.8)\ \text{A}$$

Load current in section BC, $\bar{I}_{BC} = \bar{I}_2 + \bar{I}_3$

$$= (34.16 - j20.8) + (44 - j23.75) = (78.16 - j44.55)\ \text{A}$$

Voltage at the load point B,

$$\bar{V}_B = \bar{V}_C + (\bar{I}_3 + \bar{I}_2)\bar{Z}_{BC}$$

$$= (223.009 + j1.785) + (78.16 - j44.55)(0.072 + j0.12)$$

$$= (223.009 + j1.785) + (10.973 + j6.172) = (233.982 + j7.957)\ \text{V}$$

Phase angle between V_B and V_D, $\theta_2 = \tan^{-1}\left(\frac{7.957}{233.982}\right) = 1.95°$

The load current I_1 *lags* behind the voltage V_B by an angle

$$= \cos^{-1}(0.8) = 36.87°$$

The load current I_1 lags behing the voltage at the far end V_D by an angle

$$= 36.87° - 1.95° = 34.92°$$

Load current at point B, $\bar{I}_1 = 60(\cos 34.92° - j \sin 34.92°)$

$$= 60(0.8199 - j0.5724) = (49.194 - j34.344)$$

Load current in section AB,

$$I_{AB} = \bar{I}_1 + \bar{I}_2 + \bar{I}_3$$

$$= (49.194 - j34.344) + (34.16 - j20.8) + (44 - j23.75)$$

$$= (127.354 - j78.894)$$

Voltage at sending end point A,

$$\bar{V}_A = \bar{V}_B + \left(\bar{I}_1 + \bar{I}_2 + \bar{I}_3\right)\bar{Z}_{AB}$$

$$= (233.982 + j7.957) + (127.354 - j78.894)(0.072 + j0.12)$$

$$= (233.982 + j7.957) + (18.637 + j9.602)$$

$$= (252.62 + j17.56) = 253.23\ \angle 3.98°$$

i.e., *Voltage at the sending end* = **253.23 V. Ans.**

Phase angle of sending end voltage (V_A) w.r.t.
the receiving end voltage (V_D), θ = **3.98°. (Ans.)**

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1. By Kirchhoff's laws.
2. By star-delta conversion.
3. By applying Milliman's Theorem.
4. By using Maxwell's Mesh or Loop Current Method.

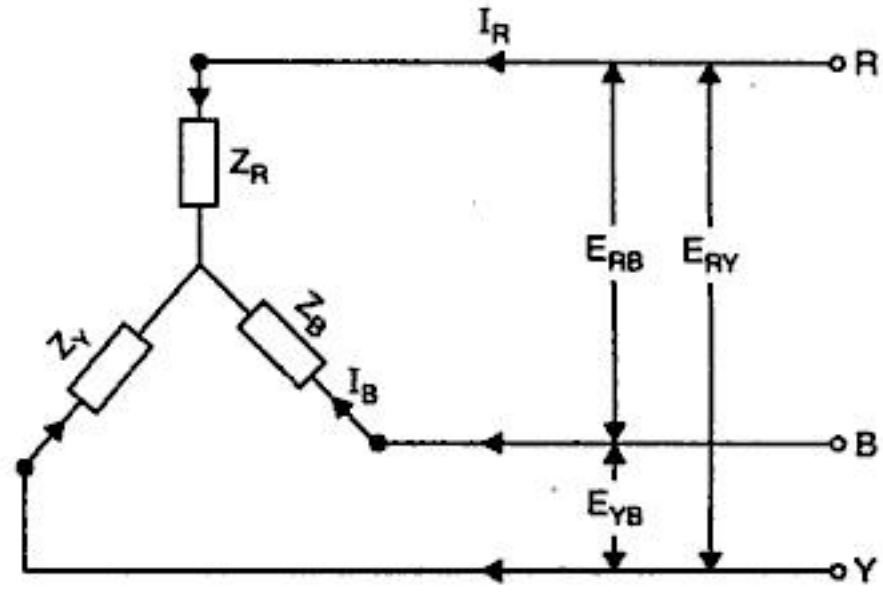

Fig. 19.92

1. Kirchhoff's laws. By applying Kirchhoff's laws, we get (Refer to Fig. 19.92)

$$E_{RY} = I_R Z_R - I_Y Z_Y \quad ...(i)$$
$$E_{YB} = I_Y Z_Y - I_B Z_B \quad ...(ii)$$
$$E_{BR} = I_B Z_B - I_R Z_R \quad ...(iii)$$
and, $$I_R + I_Y + I_B = 0 \quad ...(iv)$$

Adding (i) and (iii), we get

$$E_{RY} + E_{BR} = I_R Z_R - I_Y Z_Y + I_B Z_B - I_R Z_R$$
$$= I_B Z_B - I_Y Z_Y$$

or, $$I_B = \frac{E_{RY} + E_{BR} + I_Y Z_Y}{Z_B} \quad ...(v)$$

Substituting $I_Y + I_B = -I_R$ from (iv) in (iii), we get

$$E_{BR} = I_B Z_B + (I_Y + I_B) Z_R = I_B (Z_B + Z_R) + I_Y Z_R \quad ...(vi)$$

Substituting the value of I_B from (iv) in (vi), we get

$$E_{BR} = \left(\frac{E_{RY} + E_{BR} + I_Y Z_Y}{Z_B} \right) (Z_B + Z_R) + I_Y Z_R$$

or, $$E_{BR} Z_B = E_{RY} Z_B + E_{BR} Z_B + I_Y Z_Y Z_B + E_{RY} Z_R + E_{BR} Z_R + I_Y Z_Y Z_R + I_Y Z_R Z_B$$

or, $$I_Y (Z_R Z_Y + Z_Y Z_B + Z_B Z_R) = -Z_R (E_{RY} + E_{BR}) - E_{RY} Z_B$$

or, $$I_Y (Z_R Z_Y + Z_Y Z_B + Z_B Z_R) = Z_R E_{YB} - Z_B E_{RY} \quad (\because \; E_{RY} + E_{YB} + E_{BR} = 0)$$

or, $$I_Y = \frac{E_{YB} Z_R}{Z_R Z_Y + Z_Y Z_B + Z_B Z_R} - \frac{E_{RY} Z_B}{Z_R Z_Y + Z_Y Z_B + Z_B Z_R}$$

i.e., $$I_Y = \frac{E_{YB}}{Z_Y + Z_B + \frac{Z_Y Z_B}{Z_R}} - \frac{E_{RY}}{Z_R + Z_Y + \frac{Z_R Z_Y}{Z_B}}$$

Similarly, $$I_B = \frac{E_{BR}}{Z_B + Z_R + \frac{Z_B Z_R}{Z_Y}} - \frac{E_{YB}}{Z_Y + Z_B + \frac{Z_Y Z_B}{Z_R}}$$

and, $$I_R = \frac{E_{RY}}{Z_R + Z_Y + \frac{Z_R Z_Y}{Z_B}} - \frac{E_{BR}}{Z_B + Z_R + \frac{Z_B Z_R}{Z_Y}}$$

2. Star-delta conversion. In case of unbalanced star-connected load it is somewhat more convenient to convert it into equivalent delta-connected load and solve it.

If Z_R, Z_Y and Z_B be the impedances of the given star-connected load and Z_{RY}, Z_{YB}, Z_{BR} be the impedances of the equivalent delta-connected load (Fig. 19.93), then

$$Z_{RY} = Z_R + Z_Y + \frac{Z_R Z_Y}{Z_B} = \frac{Z_R Z_B + Z_{YB} + Z_{RY}}{Z_B}$$

$$Z_{YB} = Z_Y + Z_B + \frac{Z_Y Z_B}{Z_R} = \frac{Z_Y Z_R + Z_B Z_R + Z_Y Z_B}{Z_R}$$

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$$= 6(0.465 - j0.885) - 4(0.12 + j0.993)$$
$$= 2.79 - j5.31 - 0.48 - j3.97 = 2.31 - j9.28 = \mathbf{9.56 \angle - 76^\circ\ A.} \quad \textbf{(Ans.)}$$

$$\bar{\mathbf{I}}_Y = \bar{I}_{YB} - \bar{I}_{RY} = 8 \angle - 66.9^\circ - 6 \angle - 62.3^\circ$$
$$= 8(0.392 - j0.92) - 6(0.465 - j0.885)$$
$$= (3.136 - j7.36) - (2.79 - j5.31)$$
$$= 0.346 - j2.05 = \mathbf{2.07 \angle - 80.4^\circ\ A.} \quad \textbf{(Ans.)}$$

$$\bar{\mathbf{I}}_B = \bar{I}_{BR} - \bar{I}_{YB} = 4 \angle 83.1^\circ - 8 \angle - 66.9^\circ$$
$$= 4(0.12 + j0.993) - 8(0.392 - j0.92)$$
$$= 0.48 + j3.97 - 3.136 + j7.36$$
$$= -2.656 + j11.33 = \mathbf{11.637 \angle 103.2^\circ\ A.} \quad \textbf{(Ans.)}$$

(*iii*) **Power consumed :**

Total power is the sum of power in difference phases.

$$\therefore \quad P = E_{RY} \times I_{RY} + E_{YB} \times I_{YB} + E_{BR} \times I_{BR}$$
$$= 400 \angle 0^\circ \times 6 \angle - 62.3^\circ + 400 \angle - 120^\circ \times 8 \angle - 66.9^\circ + 400 \angle 120^\circ \times 4 \angle 83.1^\circ$$
$$= 400 \times 6 \cos(-62.3^\circ) + 400 \times 8 \cos(53.1^\circ) + 400 \times 4 \cos(-36.9^\circ)$$
$$= 1115.6 + 1921.3 + 1279.5 = 4316.4\ \text{W}$$

[Or $$P = I^2_{RY} R_{RY} + I^2_{YB} \times R_{YB} + I^2_{BR} \times R_{BR}$$
$$= 6^2 \times 31 + 8^2 \times 30 + 4^2 \times 80 = 1116 + 1920 + 1280 = 4316\ \text{W}]$$

Hence, **total power = 4316. W. (Ans.)**

HIGHLIGHTS

1. That part of the network of a power system which distributes power for local use is known as *distribution system.*
2. The following are the requirements of a good distribution system :
   (*i*) Proper voltage ; (*ii*) Availability of power on demand ;
   (*iii*) Reliability.
3. The various types of distributors are :
   (*i*) Distributors fed at one end (*ii*) Distributors fed at both ends
   (*iii*) Distributors fed at the centre (*iv*) Ring distributor.
4. A distributor which is arranged to form a closed circuit and which is fed at one or more than one points is called a *ring distributor.*
5. The various methods used to supply a 3-wire D.C. system are :
   (*i*) The two-generator method (*ii*) The balancer set
   (*iii*) The single-generator tapped-resistor (*iv*) The Dabrowolsky generator method
   (*v*) The synchronous converter.
6. In a 3-wire D.C. system to transmit the same amount of power with the same efficiency over same distance with same consumer voltage we require $\frac{5}{16}$ th or 0.3125 times copper as required in 2-wire D.C. system.
7. The line bringing electric power from supplier's low voltage distributor upto the energy meter installed at the consumer's premises is called the *service connection.*
8. In A.C. system the voltage drops are due to the combined effects of resistances, inductances and capacitances.

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— To date the biggest H.V.D.C. transmission is ITAIPU in Brazil (two bipoles, 6300 MW and ± 300 kV).
— In India the first H.V.D.C. line is Rihand-Delhi (± 500 kV, 800 MW).
— The highest voltage transmission reached is ± 600 kV.

20.2. EXTRA HIGH VOLTAGE A.C. TRANSMISSION

Use of E.H.V. A.C. transmission is increasing day by day for interconnections of two or more power systems to achieve sharing of installed reserves ; construction of large power plants, and for development of integrated systems and grids.

20.2.1. Advantages of E.H.V. Transmission

The following are the *advantages* of E.H.V. A.C. transmission for transmitting bulk power over long distances :

1. With the increase in transmission voltage, the *transmission efficiency increases* for a given amount of power to be transmitted over a given distance (line losses are reduced since these are inversely proportional to the transmission voltage).

2. *Voltage regulation is improved* because of reduction in line losses.

3. *The volume of conductor material decreases*, being *inversely* proportional to the square of transmission voltage.

4. The transmission capacity of the line *increases* tremendously, since the transmission capacity is proportional to the square of the operating voltages.

Although the costs of the tower, installation and terminal equipments increase but in general use these costs are proportional to the voltages rather than square of the transmission voltage. Consequently, *overall capital cost of transmission decreases as the voltage increases.*

5. With the increase in voltage level, the *installation cost* of the transmission line per km *decreases.*

6. Since Surge Impedance Loading (SIL) is proportional to the square of the voltage $\left(P_{SIL} = \frac{V^2}{Z_0}, \text{ where } Z_0 \text{ is the surge impedance of line}\right)$, therefore, with increase of voltage level, *SIL* itself increases which indicates that *power transfer increases.*

7. The interconnections of the power systems on a large scale is possible with EHV transmission only.

8. Flexibility for future system growth.

9. Reduction in rights of way.

20.2.2. Limitations/Problems involved in E.H.V. Transmission

Following are some *limitations / problems involved in E.H.V. transmission* :

1. Corona loss and radio interference.
2. Heavy supporting structures and erection difficulties.
3. Insulation requirements.
4. Suitability considerations.
5. Current carrying capacity.
6. Ferranti effect.
7. Environmental and biological aspects.

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PART–III : SWITCHGEAR AND PROTECTION

Chapters :

21. Symmetrical Components and Fault Calculations
22. Switches, Fuses and Circuit Breakers
23. Protective Relays
24. Protection of Alternators and Transformers
25. Protection of Bus-bars and Lines/Feeders
26. Protection Against Overvoltages and Insulation Co-ordination
27. Neutral Earthing (Grounding)
28. Sub-stations

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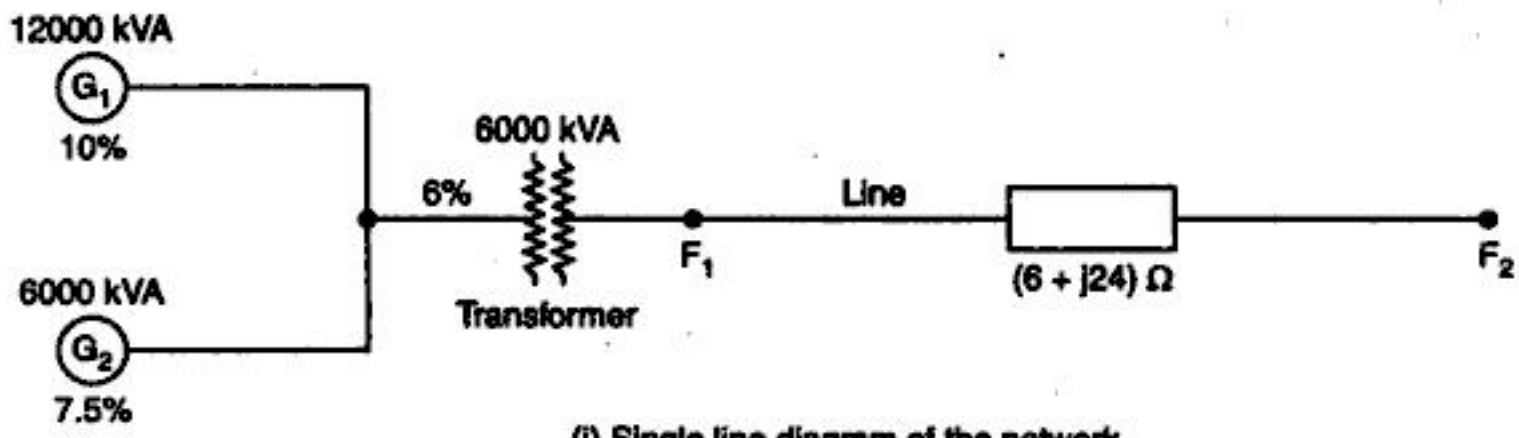
As the transformers are assumed to be ideal, hence, the impedances of these are neglected.

Then, $$Z_{total} = Z_{line} + Z_{load}$$
$$= (0.01 + j0.02) + (3 + j6) = (3.01 + j6.02) \text{ p.u.}$$
$$= 6.73 \angle 63.43°$$

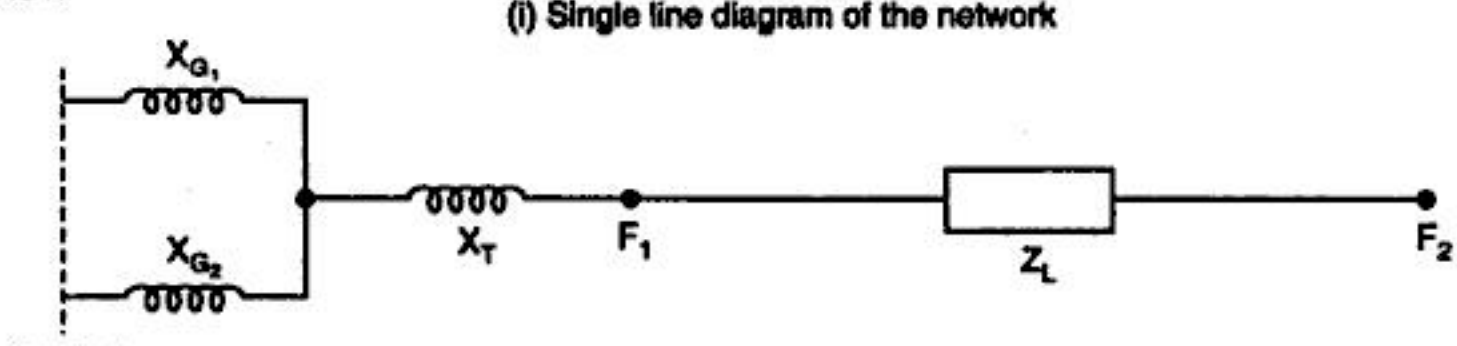
Per unit current, $$\mathbf{I} = \frac{1 \angle 0°}{Z_{total}} = \frac{1 \angle 0°}{6.73 \angle 63.43°} = \mathbf{0.1486 \angle -63.43° \text{ p.u.}} \quad \textbf{(Ans.)}$$

Example 21.3. *A 3-phase transmission line operating at 33 kV and having a resistance and reactance of 6 ohms and 24 ohms respectively is connected to the generating station bus-bar through a 6000 kVA step-up transformer which has a reactance of 6%. Connected to the bus-bars are two synchronous generators, one 12000 kVA having 10% reactance, and another 6000 kVA having 7.5% reactance. Calculate the kVA at short-circuit fault between phases occuring at the high voltage terminals of the transformers and at load end of transmission line.*

Solution. The single line diagram of the network is shown in Fig. 21.8 (*i*).



(i) Single line diagram of the network



(ii) Single line impedance diagram

(iii) Simplified impedance diagram

Fig. 21.8

Choosing 12000 kVA as base *kVA*, we have :

Reactance of generator G_1, $X_{G_1} = 10\%$

Reactance of generator G_2, $X_{G_2} = 7.5 \times \frac{12000}{6000} = 15\%$

Reactance of transformer, $X_T = 6 \times \frac{12000}{6000} = 12\%$

The line impedance in ohms can be converted to percentage impedance (using eqn. 21.3) as follows :

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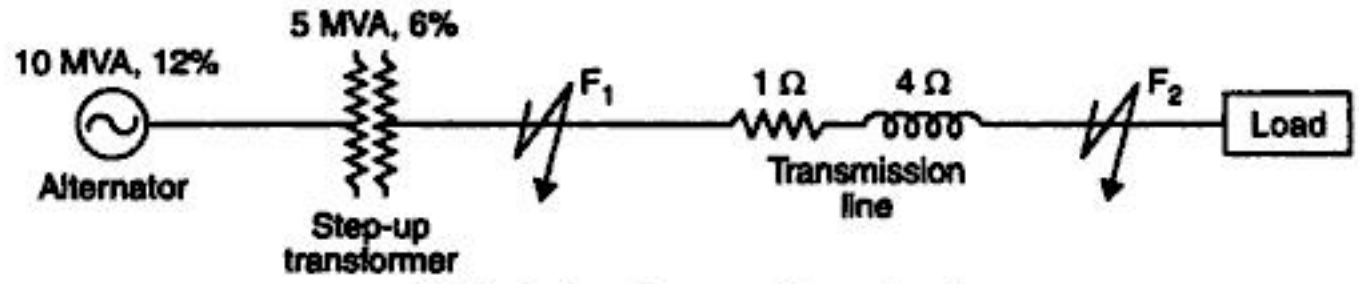
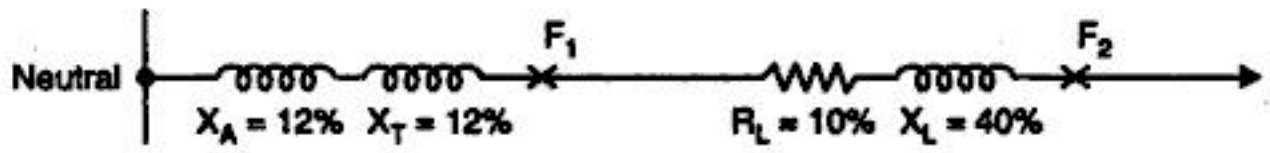


(a) Single line diagram of the network



(b) Impedance diagram of the network

Fig. 21.12

The line impedance is given in ohms. It can be converted into percentage impedance (by using eqn. 21.3) as follows :

% Resistance of transmission line,

$$\% R_L = \frac{R\,(\text{kVA})}{10\,(\text{kV})^2} = \frac{1 \times 10000}{10 \times (10)^2} = 10\%$$

$$\% X_L = \frac{X\,(\text{kVA})}{10\,(\text{kV})^2} = \frac{4 \times 10000}{10 \times 10^2} = 40\%$$

The impedance diagram of the network is shown in Fig. 21.12 (*b*).

(*i*) *Fault at the high voltage terminals of the transformer (Point F_1) :*

Total % reactance from alternator neutral upto fault point F_1

$$= \% X_A + \% X_T = 12 + 12 = 24\%$$

$\therefore$ *Short-circuit kVA* $= 10000 \times \frac{100}{24} = 41667$ **kVA. (Ans.)**

(*ii*) *Fault at the load end of transmission line (Point F_2) :*

$$\text{Total \% reactance} = \% X_A + \% X_T + \% X_L$$
$$= 12 + 12 + 40 = 64\%$$

$$\% \text{ Resistance} = 10\%$$

$\therefore$ % Impedance from alternator neutral upto fault point F_2

$$= \sqrt{(64)^2 + (10)^2} = 64.78\%$$

$\therefore$ *Short circuit kVA* $= 10000 + \frac{100}{64.78} = 15437$ **kVA. (Ans.)**

Example 21.10. *The plant capacity of a 3-phase generating station consists of two 12000 kVA generator of reactance 10% each and one 6000 kVA generator of reactance 15%. The generators are connected to the station bus-bars from which load is taken through three 6000 kVA step-up transformers each having a reactance of 5%. Determine the maximum fault MVA which the circuit breakers on (i) low voltage side and (ii) high voltage side may have to deal with.*

Solution. Fig. 21.13 shows the single line diagram of the network.

Let 12000 kVA be the base kVA.

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% Reactance of each generator (G_1, G_2, G_3 and G_4) on the base MVA

$$= 10 \times \frac{8}{8} = 10\%$$

% Reactance of the reactor on the base MVA

$$= 20 \times \frac{8}{8} = 20\%$$

% Reactance of the transformer on the base MVA

$$= 5 \times \frac{8}{5} = 8\%$$

When fault occurs at F, the reactance diagram on the selected base MVA will be as shown in Fig. 21.31 (a). This further reduces to the arrangement of the reactances shown in Fig. 21.31 (b).

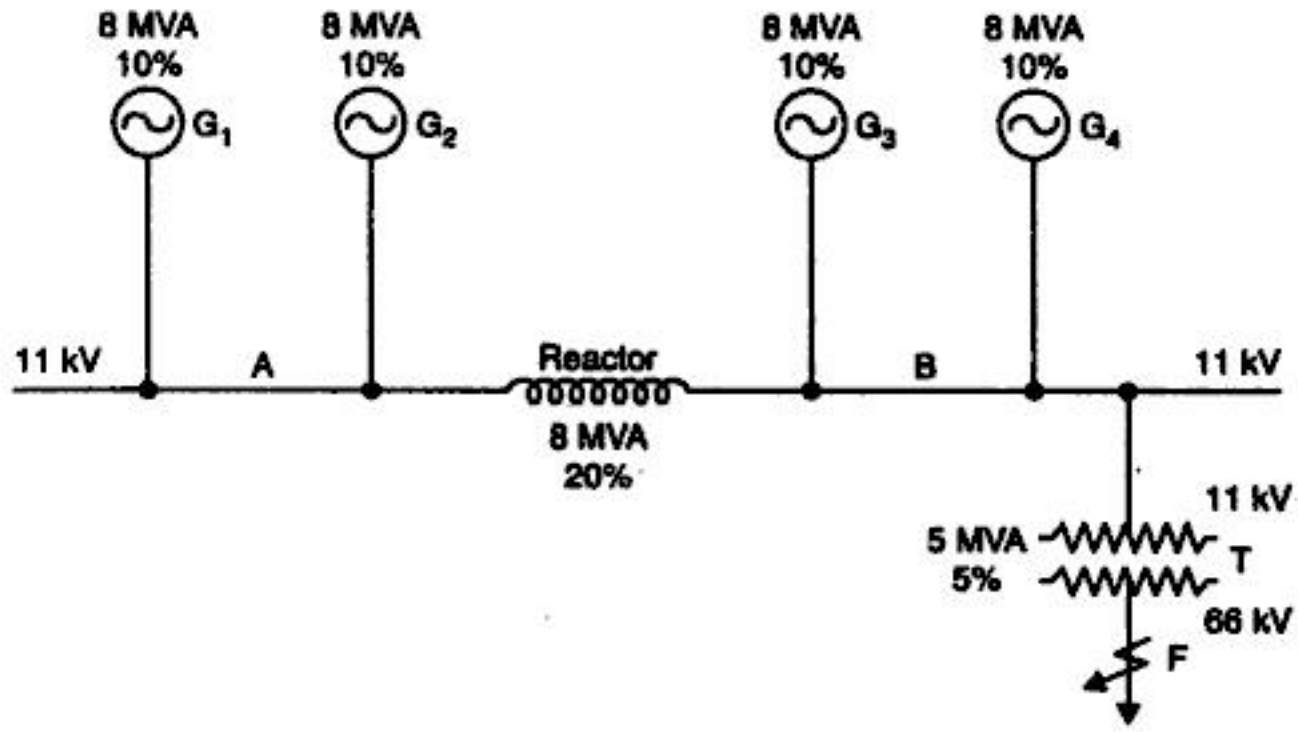

Fig. 21.30. Single line diagram of the network.

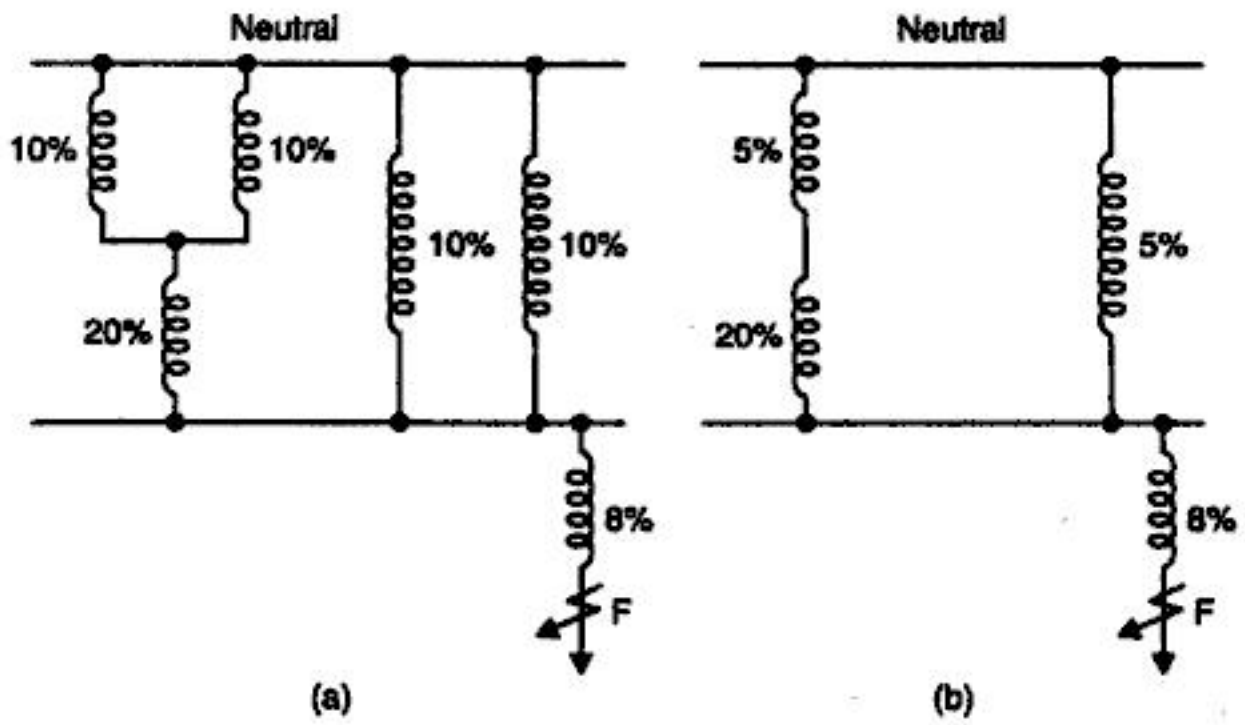

Fig. 21.31. Reactance diagram.

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$$\% \text{ Reactance of line} = 100 \times \frac{24}{(120)^2} \times 100 = 16.7\%$$

Negative sequence network :

The network is exactly identical to positive sequence network except for the sources.

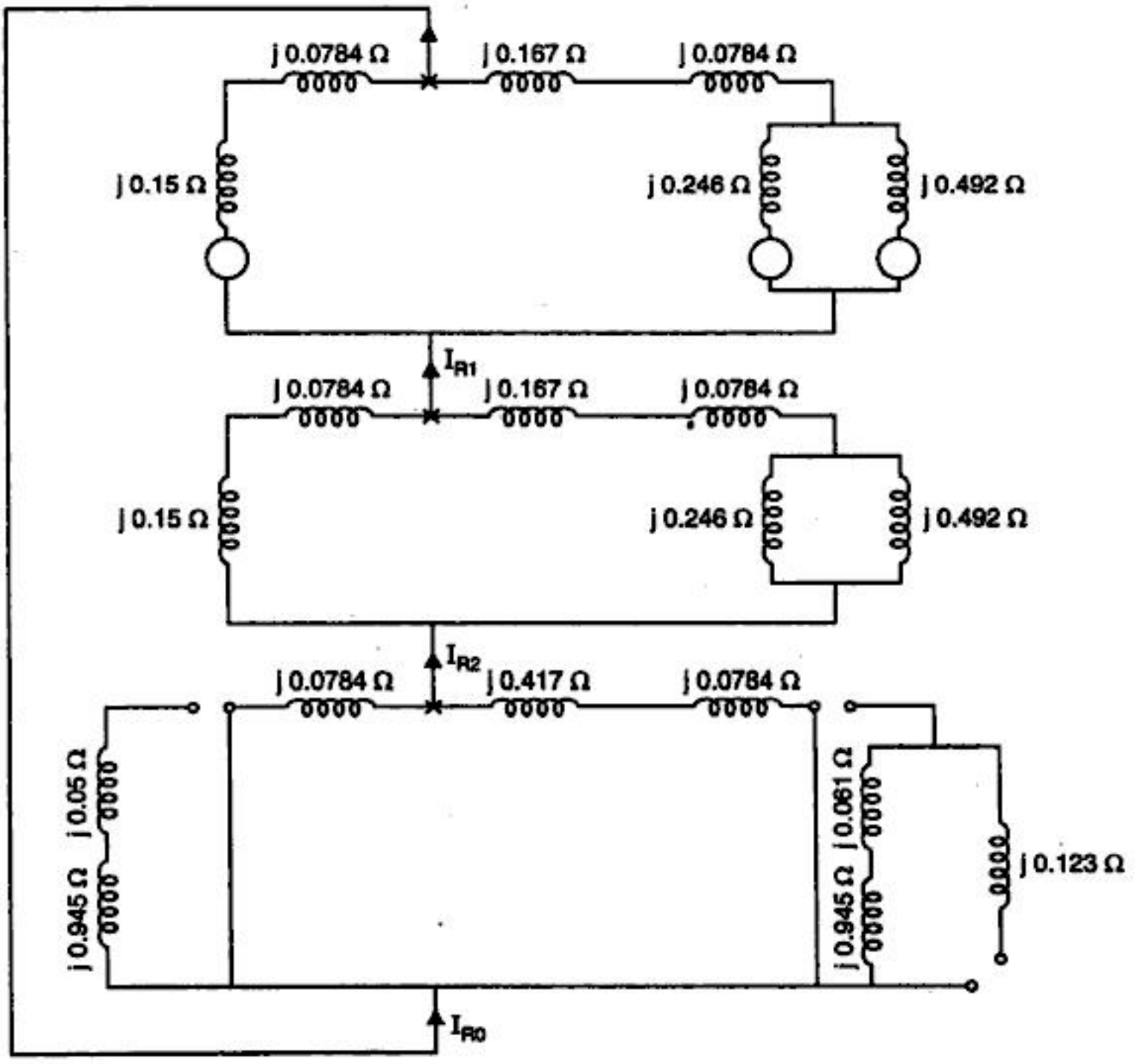

Fig. 21.83. Positive, negative and zero sequence networks.

Zero sequence network :

$$\text{The neutral reactance} = 2.5 \times 3 \times \frac{24}{(13.8)^2} \times 100 = 94.5\%$$

$$\text{The zero sequence reactance of line} = 250 \times \frac{24}{(120)^2} \times 100 = 41.7\%$$

The three sequence networks are shown in Fig. 21.83.

Positive sequence impedance between P and ZPB (when sources are short circuited),

$$\bar{Z}_1 = (j0.15 + j0.0784) \parallel [(j0.167 + j0.0784) + (j0.246 \parallel j0.492)]$$

$$= j0.2284 \parallel [j0.2454 + j0.164] = j0.2284 \parallel j0.4094 = j0.147\ \Omega$$

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22

Switches, Fuses And Circuit Breakers

22.1. **Switchgear—general aspects**—Definition of switchgear—Functions of switchgear—Essential features of switchgear—Principles of layout of switchgear—Types of switchgear—Short-circuits in electrical installations and limiting methods. 22.2. **Switches.** 22.3. **Fuses**—Definition of fuse—Advantages and disadvantages of a fuse—Desirable characteristics of fuse element—Fuse element materials—Important terms relating to fuses—Types of fuses—Fuse selection—Difference between sub-circuit fuses, main circuit fuses, meter board fuses and pole fuses in an electrical installation—Difference between fuse and circuit breaker. 22.4. **Circuit breakers**—Introduction—Functions of a circuit breaker—Principle of circuit breaker—Arc phenomenon—Methods of arc extinction—Arc, restriking and recovery voltages—Current chopping—Resistance switching—Classification of circuit breakers—Oil circuit breakers—Water type circuit breaker—Air blast circuit breakers—Sulphur hexafluoride (SF_6) circuit breakers—Vacuum circuit breakers—Low voltage circuit breakers—Ratings of circuit breakers—Testing of circuit breakers—Autoreclosing—Maintenance of circuit breakers—Switchgear components—Bus-bar arrangements. 22.5. Control room—power station. Highlights—Theoretical Questions—Unsolved Examples.

22.1. SWITCHGEAR—GENERAL ASPECTS

22.1.1. Definition of Switchgear

Switchgear is *a term which covers wide range of equipment as regards switching and interrupting the currents in the power system during normal and abnormal conditions.*

Or

The apparatus used for switching, controlling and protecting the electrical circuits and equipment is known as **switchgear.**

"Switchgear" in general *consists of the following :*

(*i*) Switches
(*ii*) Fuses
(*iii*) Circuit breakers
(*iv*) Isolators
(*v*) Relays
(*vi*) Control panels
(*vii*) Metering panels
(*viii*) Lightning arrestors
(*ix*) Current transformers
(*x*) Potential transformers etc.

22.1.2. Functions of Switchgear

The *functions* performed by a switchgear are listed below :

1. To localise the effects of faults by operation of protective equipment and so automatically disconnect faulty point from the system.

2. To break efficiently short circuits without giving rise to dangerous conditions.

3. To facilitate redistribution of loads, inspection and maintenance on the system.

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Disadvantages :

1. Time is lost in replacing fuse after operation.
2. On heavy short-circuits discrimination between fuses in series cannot be obtained unless there is considerable difference in the relative sizes of the fuses concerned.
3. The current-time characteristic of a fuse cannot always be co-related with that of the protected apparatus.

22.3.3. Desirable Characteristics of Fuse Element

The fuse element should possess the following *desirable characteristics* :

1. Low melting point.
2. Low ohmic losses.
3. High conductivity.
4. Free from deterioration due to oxidation.
5. Low cost.

Since all the characteristics are not available in a single material, therefore, compromise is made in the selection of fuse material.

22.3.4. Fuse Element Materials

Lead, *tin*, *copper*, *zinc* and *silver* are the most commonly used materials for fuse elements.

- For *small currents* upto 10 A, tin or an alloy of lead and tin (lead 37%, tin 63%) is used for making the fuse element.
- For *large currents*, copper or silver is employed.
  — It is usual practice to tin the copper to protect it from oxidation.
- Zinc, in strip form only, is good if a fuse with a considerable time-lag is required *i.e.*, one which does not melt very quickly with a small overload.

The present trend is to use "*silver*" despite its high cost due to the following *reasons* :

(*i*) It does not deteriorate when used in dry air.

(*ii*) It is comparatively free from oxidation.

(*iii*) Due to its very small coefficient of expansion no critical fatigue occurs and as such the fuse element can carry the rated current continuously for a long time.

(*iv*) Silver vaporises at a temperature much lower than the one at which its vapour will readily ionise. Therefore, when an arc is formed through the vaporised portion of the element, the arc path has high resistance ; consequently, the short-circuit current is quickly reduced.

(*v*) Due to its low specific heat silver fusible elements can be raised from normal operating temperature to vaporisation very much quicker than other fusible elements. Also, as the temperature of the silver reaches the melting point its resistance increases abruptly and thus the transition from melting to vaporisation becomes nearly instantaneous. As a result, operation becomes very much faster at higher currents.

(*vi*) Due to heavy conductivity of silver, the mass of silver metal required, for a given rating of fuse element, is smaller than that of other materials. This minimises the problem of clearing the mass of vaporised material set free on fusion and thus permits fast operating speed.

22.3.5. Important Terms relating to Fuses

The important terms relating to fuses are discussed below :

1. **Current rating of fuse element.** *It is the current which the fuse element can carry without overheating or melting.*

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Under normal operating conditions, the current through the relay coil is such that the counterweight holds the armature in the balanced position as shown in the figure. However, when a fault takes place, the current through the relay coil increases considerably and the relay armature is attracted upwards. Subsequently, the stationary contacts attached to the relay frame are bridged and trip circuit is completed.

Usually a numbers of tappings on the relay coil are provided so that the number of turns in use and the setting value at which the relay operates can be varied.

The minimum current at which the relay armature is attracted to close the trip circuit is called *pick-up current.*

23.4.2. Solenoid Type Relay

Fig. 23.6 shows the schematic arrangement of a solenoid type relay. It consists of a solenoid and movable iron plunger arranged as shown.

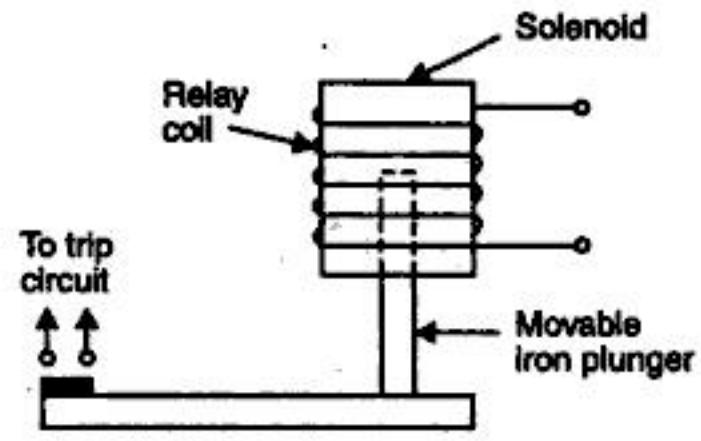

Fig. 23.6. Solenoid type relay.

Under normal working conditions, the current through coil is such that it holds the plunger by gravity or spring in the position shown. However, when a fault occurs, the current through the relay coil exceeds the pick-up value, causing the plunger to be attracted to the solenoid. The upward movement of the plunger closes the trip circuit, consequently circuit breaker opens and the faulty circuit is disconnected.

23.4.3. Balanced Beam Type Relay

The schematic arrangement of a balanced beam type relay is shown in Fig. 23.7. It consists of an armature fastened to a balance beam.

Under normal working conditions, the current through the coil is such that the beam is held in the horizontal position by the spring.

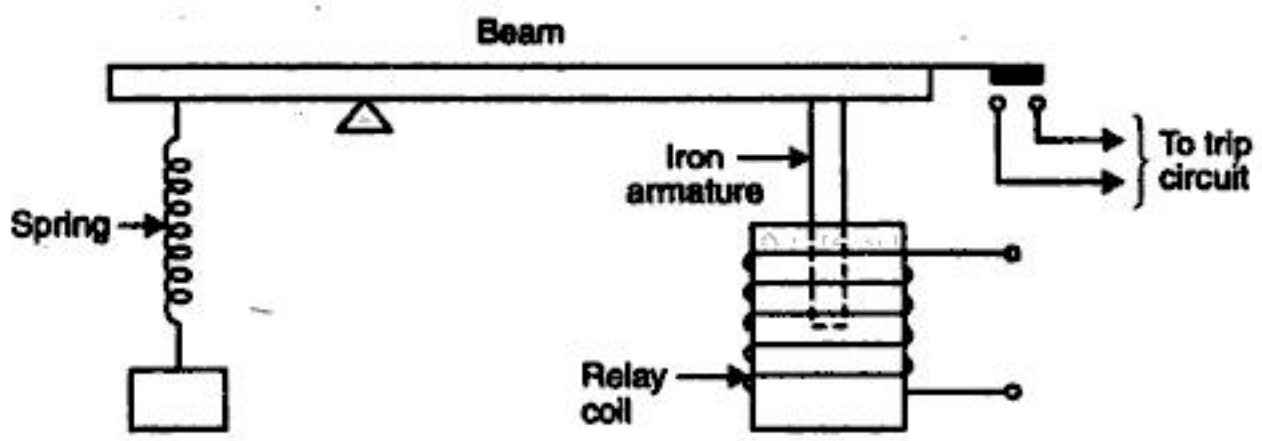

Fig. 23.7. Balanced beam type relay.

However, when a fault takes place, the current through the relay coil becomes more than the pick-up value and the beam is attracted to close the circuit. Consequently the circuit breaker opens and the faulty circuit is isolated.

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where T, V, I and C are torque, voltage, current and a constant respectively. This is nothing but an equation of circle having a centre which is *offset from the region.*

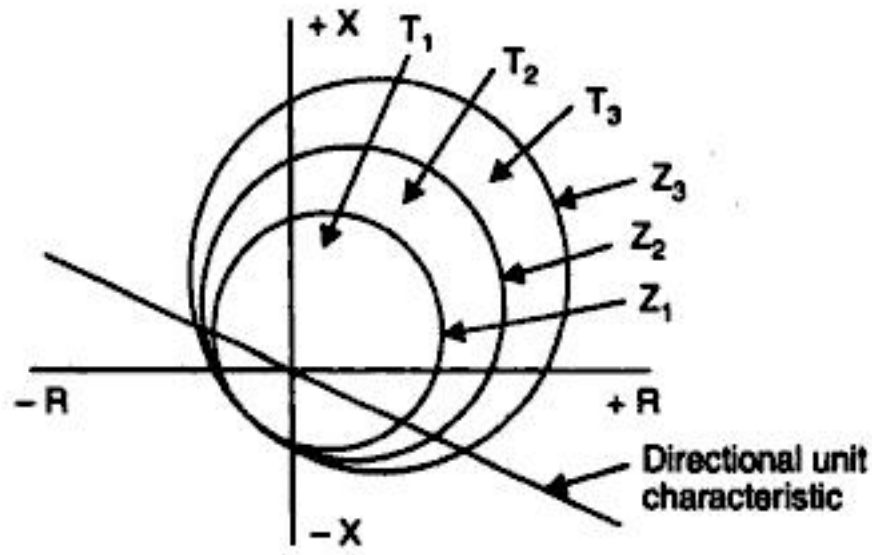

Fig. 23.35. Operating characteristic of a modified impedance-type distance relay.

23.13.2. Time-distance Impedance Relay

This type of relay automatically adjusts its operating time according to the distance of the relay from the fault point *i.e., operating time,* $T \propto \frac{V}{I} \propto Z \propto$ *Distance*

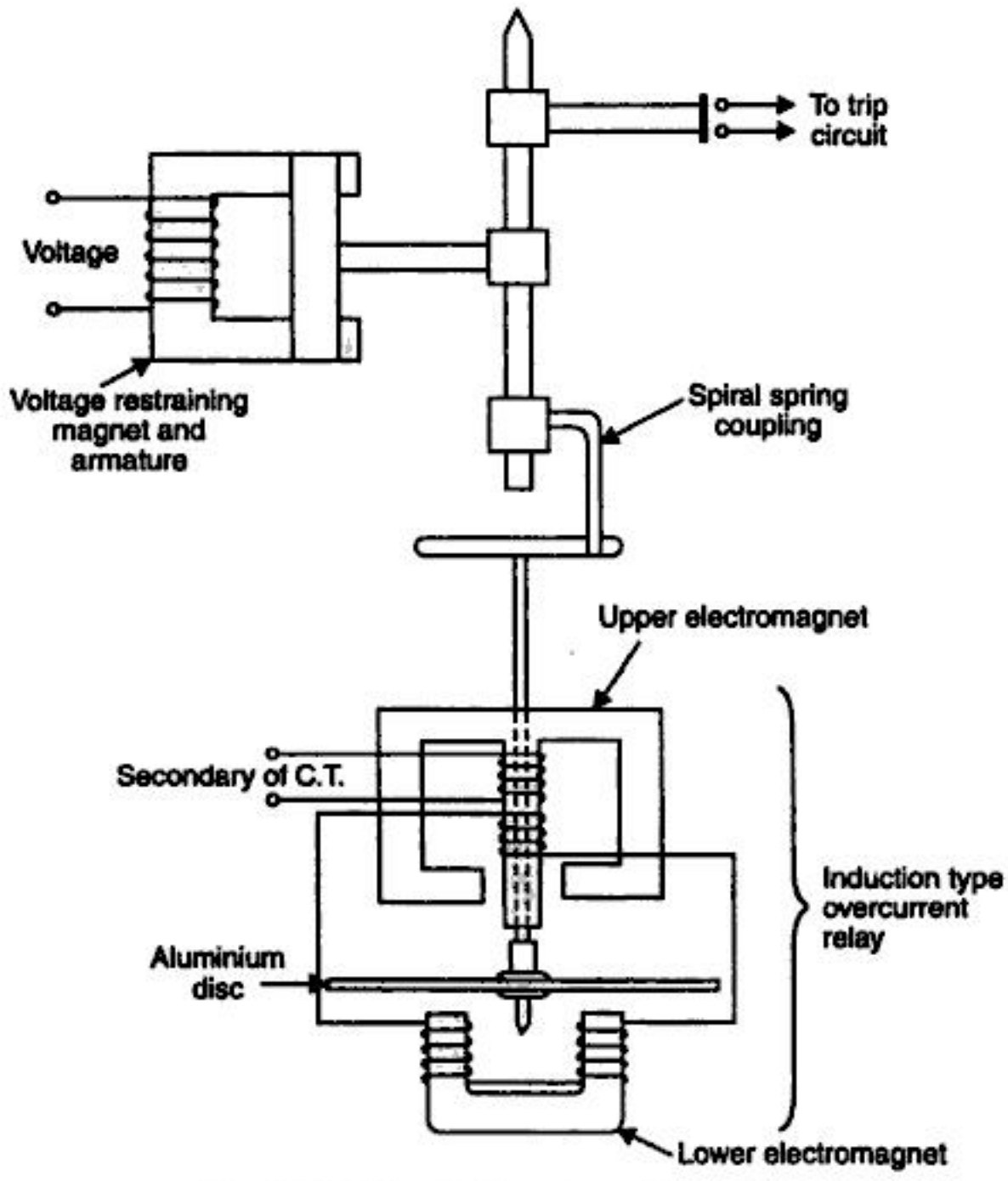

Fig. 23.36. Time-distance impedance relay.

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circulating current principle (described in article 24.1.2) and protection is provided against earth faults only by the use of balanced earth fault protection system. This system provides no protection against phase-to-phase faults, unless and until they develop into earth-faults, as most of them will.

Schematic arrangement. Fig. 24.3 shows the schematic arrangement of balanced earth fault protection for a 3-phase alternator. It consists of the line current transformers (C.Ts.), one mounted in each phase, having their secondaries connected in parallel with that of a single current transformer (C.T.) in the conductor joining the star point of the alternator to earth. A relay is connected across the transformer secondaries. The protection against earth faults is limited to the region between the neutral and the line current transformers.

Working :

- Under normal operating conditions (when the windings are sound), the secondary currents in three current transformers (C.Ts.) sum up to zero at the points *AB* while the secondary current in the single transformer (C.T.) is also zero ; thus no current flows through the relay.
- When an earth fault occurs at F_1 or within the protected zone (*i.e.* left of C.Ts.), the fault current passes through the primary of C.T. and the corresponding secondary current passes through the relay. Subsequently the relay closes its contacts to disconnect the alternator from the system.

However, if an earth fault occurs at F_2 (external to the protected zone) the current passes through the primary winding of the appropriate current transformer (C.Ts.) and also through C.T. Thus the two secondary currents are balanced and no current passes through the relay, and it does not operate.

24.1.4. Stator Inter-turn Protection

Merz-Price protection system does not provide protection against short-circuit between turns on the same phase, since this condition does not cause unbalance between currents in C.Ts. pairs. However, it is considered unnecessary to have such protection since short-circuits between turns on the same phase invariably develop into earth fault.

The coils of modern large steam-turbine generators usually have one turn and hence they do not require turn-to-turn protection.

Inter-turn protection is used for multi-turn generators, such as large hydro-electric generators. In case of large generators, stator windings are sometimes duplicated in order to carry heavy current.

Fig. 24.4 shows the inter-turn protection arrangement. The circuits are divided into two equal parallel groups with a current transformer (C.T.) for each group. S_1 and S_2 are the duplicate stator windings of one phase only (with a provision against inter-turn faults).

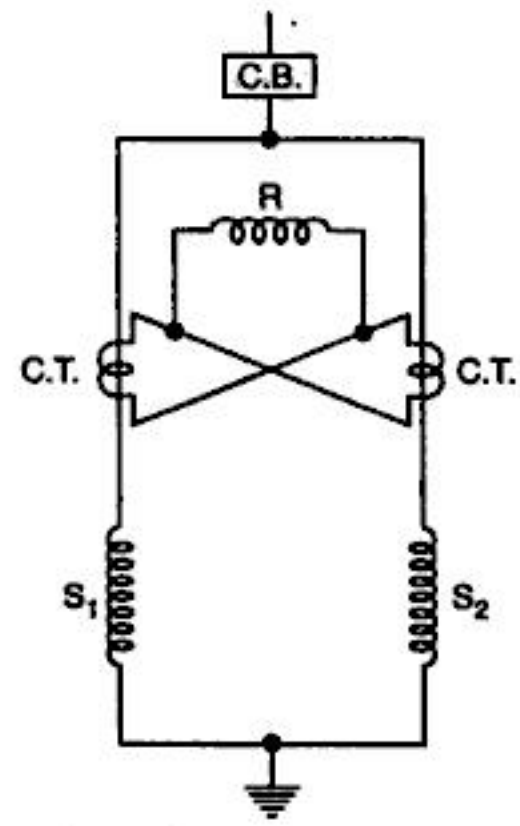

Fig. 24.4. Inter-turn protection.

- Under normal operating conditions, the currents in the stator windings S_1 and S_2 are equal and so will be the currents in the secondaries of the two C.Ts. The secondary current round the loop then is same at all points and no current flows through the relay R. If a short-circuit develops between adjacent turns, say on S_1, the currents in the stator windings S_1 and S_2 will no longer be equal and a current proportional to the difference will be diverted into the relay operating coil which will close the trip circuit and isolate the alternator from the system.

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On neglecting the alternator reactance, we have

$$\frac{63.5x}{6.0 + \frac{0.84x}{100}} = 629.8$$

or, $$63.5x = \left(6.0 + \frac{0.84x}{100}\right) \times 629.8 = 3778.8 + 5.29x$$

$\therefore$ $$\mathbf{x = 64.9\%.} \quad \textbf{(Ans.)}$$

Example 24.7. *A 11 kV, 3-phase turbo-alternator has a maximum rating of 120 MW at 0.8 p.f. and its reactance is 0.12 p.u. It is equipped with differential current protection scheme. It is set to operate at fault current not less 600 A. Determine the magnitude of the neutral earthing resistance that leaves the 12% of the winding unprotected.*

Solution. Turbo-alternator voltage = 11 kV
Maximum rating = 120 MW at 0.8 p.f.
Alternator reactance = 0.12 p.u.
Minimum operational fault current, i = 600 A
Percentage of unprotected winding = 12%

Magnitude of the neutral earthing resistance, r :

Rated current of the alternator, $I = \dfrac{120 \times 10^6}{\sqrt{3} \times 11000 \times 0.8} = 7873$ A

Relay setting, $$s = \frac{i}{I} = \frac{600}{7873} = 0.0762$$

Portion of the winding unprotected = $\dfrac{sI}{I_n}$

$\therefore$ $$0.12 = \frac{0.0762 \times 7873}{I_N}$$ (where, I_N is the current through neutral)

or $$I_N = \frac{0.0762 \times 7873}{0.12} = 4999.36 \text{ A}$$

Hence, earthing resistance, $r = \dfrac{V}{I_N} = \dfrac{11000}{\sqrt{3} \times 4999.36} = \mathbf{1.27\ \Omega.}$ **(Ans.)**

24.1.5. Unbalanced loading of the Alternator

Unbalanced loading of the stator winding *develops negative phase sequence components of currents in itself.* This causes *additional heating of the stator winding*, which is not recommended for the sake of life of alternator. Negative sequence current protection scheme is mostly applied in order to sense degree of unbalancing in stator current.

24.1.6. Overload (or Overcurrent) Protection

For alternators, overcurrent protection is not considered necessary, since modern alternators are capable of withstanding their complete short-circuit current for sufficient time without serious overheating and damage. On such faults these are disconnected manually.

24.1.7. Failure of Prime-mover

When the input to the prime-mover fails, the alternator runs as a synchronous motor and draws some current from the supply system. This motoring condition is known as ***"inverted running"***.

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Ratio of C.Ts. on the high-voltage side :

For star-delta transformers, C.Ts. will be connected in delta for star-side power transformer (*i.e.*, on 220 V side) and in star for delta side of power transformer (*i.e.*, on 11000 V), as shown in Fig. 24.15. Assume that line current on 220 V side is 500 A.

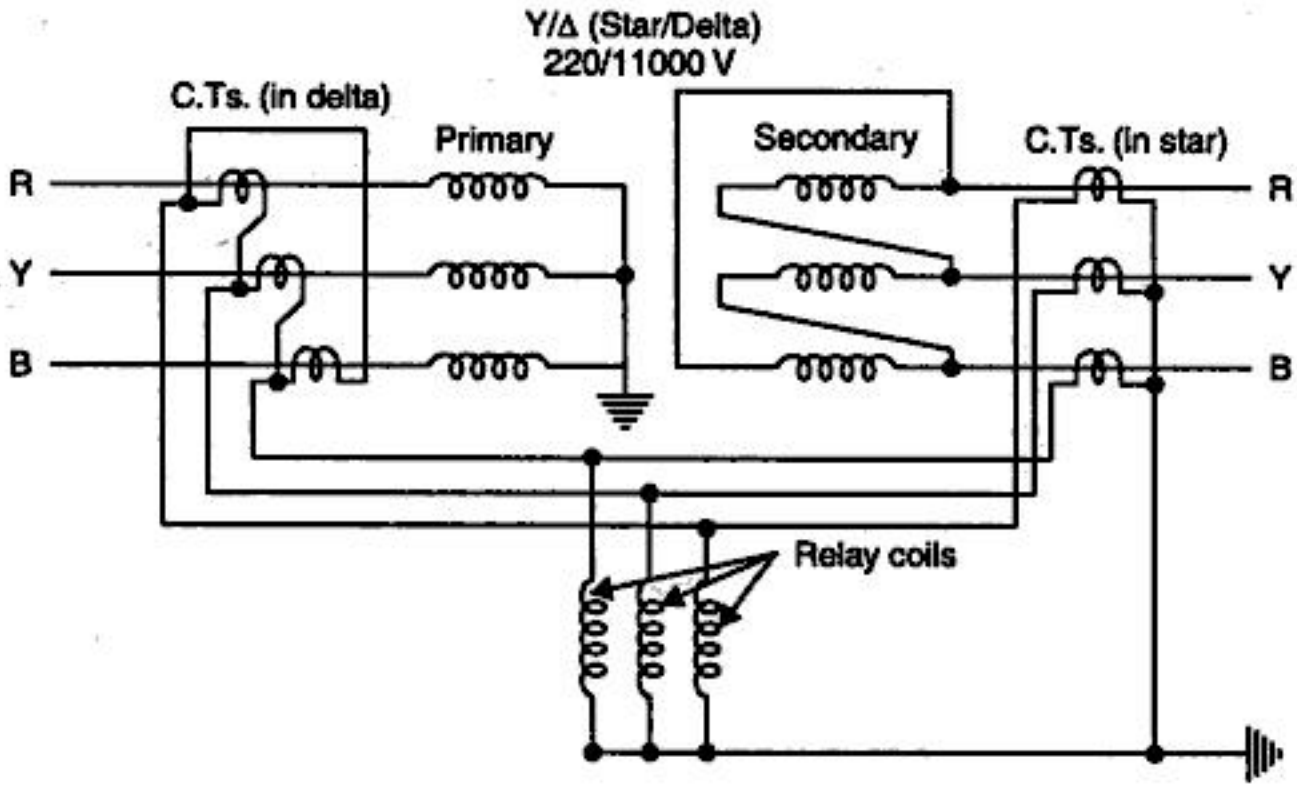

Fig. 24.15

∴ Phase current of delta-connected C.Ts. on 220 V side = 5 A

Line current of delta-connected C.Ts. on 220 V side = $\sqrt{3} \times 5 = 5\sqrt{3}$ A. This current of $5\sqrt{3}$ A will flow through the pilot wires. Obviously this will be the current which flows through the secondary of C.Ts. on the 11000 V side.

∴ Phase current of star-connected C.Ts. on 11000 V side = $5\sqrt{3}$ A

If I is the *line current* on 11000 V side, then,

Primary apparent power = Secondary apparent power

or, $$\sqrt{3} \times 220 \times 500 = \sqrt{3} \times 11000 \times I$$

or, $$I = \frac{\sqrt{3} \times 220 \times 500}{\sqrt{3} \times 11000} = 10 \text{ A}$$

∴ Turn-ratio of C.Ts. on 11000 V side

$$= 10 : 5\sqrt{3} = \mathbf{1.155 : 1.} \quad \textbf{(Ans.)}$$

Example 24.9. *A 120 MVA, delta / star connected, 11 / 220 kV transformer is to be protected by percentage differential scheme. C.Ts. used are of 5000 / 5 and 400 / 1 respectively. Draw the sketch of complete scheme.*

Solution. Rating of transformer = 120 MVA ; delta/star connected ; 11/220 kV

Ratio of C.Ts. on L.V. side = 5000/5

Ratio of C.Ts. on H.V. side = 400/1

Rated current for star (220 kV) side

$$= \frac{120 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 314.9 \text{ A}$$

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Schemes of bus-bar protection :

The various schemes of bus-bar protection are :

1. Differential protection (Bus protective by differential relays)
2. Fault bus protection.
3. Bus protection by overcurrent relays.
4. Static protection.
5. Overcurrent protection or distance protection as back up protection of bus-bar.

25.2.1. Differential Protection

This system of protection of the bus-bars is extensively used in modern power station or substations.

In this system the currents entering and leaving the bus are totalised. Under normal operating conditions, the sum of these currents is zero. However, on occurence of the fault, the fault current upsets the balance and produces a differential current which operates a relay.

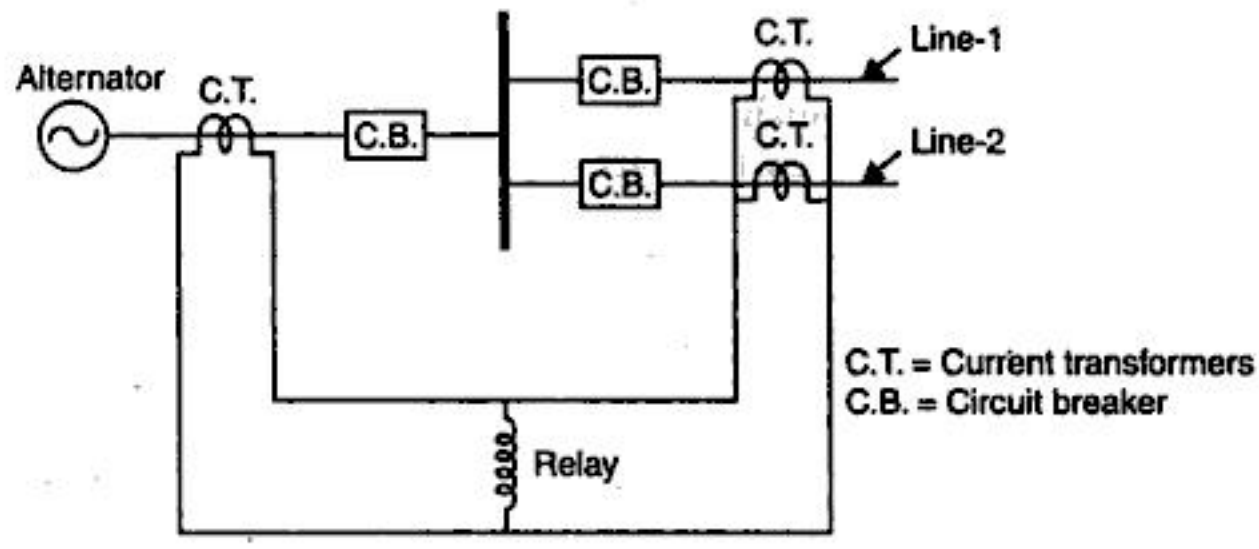

Fig. 25.1. Differential protection–Station bus-bar.

Fig. 25.1 shows the schematic arrangement of differential (circulating current) protection to a station bus-bar. The secondaries of C.Ts. in the alternator load in line-1 and line-2 are connected in parallel. The protective relay is connected across this parallel connection. Regardless of the capacities of the various circuits, *all C.Ts. must be of the same ratio* in the scheme.

Under *normal load conditions* (or external fault conditions), the sum of the currents entering the bus is *equal* to those leaving it and no current flows through the relay and it remains inoperative.

However, when fault occurs within the protected zone, the currents entering the bus will no longer be equal to those leaving it. The differential current (difference of entering and outgoing currents) will flow through the relay and cause opening of generator circuit breaker and each of the line circuit breakers.

- Circulating current protection to bus-bar can be *adopted to discriminate operation on duplicate bus-bar*. In this case *auxiliary switches* are mounted on the bus-bar selector switches of each equipment and so connected that the current transformer residual circuit of the equipments connected to the same set of bus-bars are parallel to the bus-bar protective relay controlling that particular zone.

25.2.2. Fault Bus Protection

The design of such a station in which the faults that develop are mostly earth faults is feasible by *providing earthed metal barrier* (known as *fault bus*) surrounding each conductor throughout its length in the bus structure. In such an arrangement every fault that might occur *must involve a connection between a conductor and an earthed metal. The faults can be detected and located by directing the flow of earth-fault current. Such a scheme of protection is called* **fault bus protection.**

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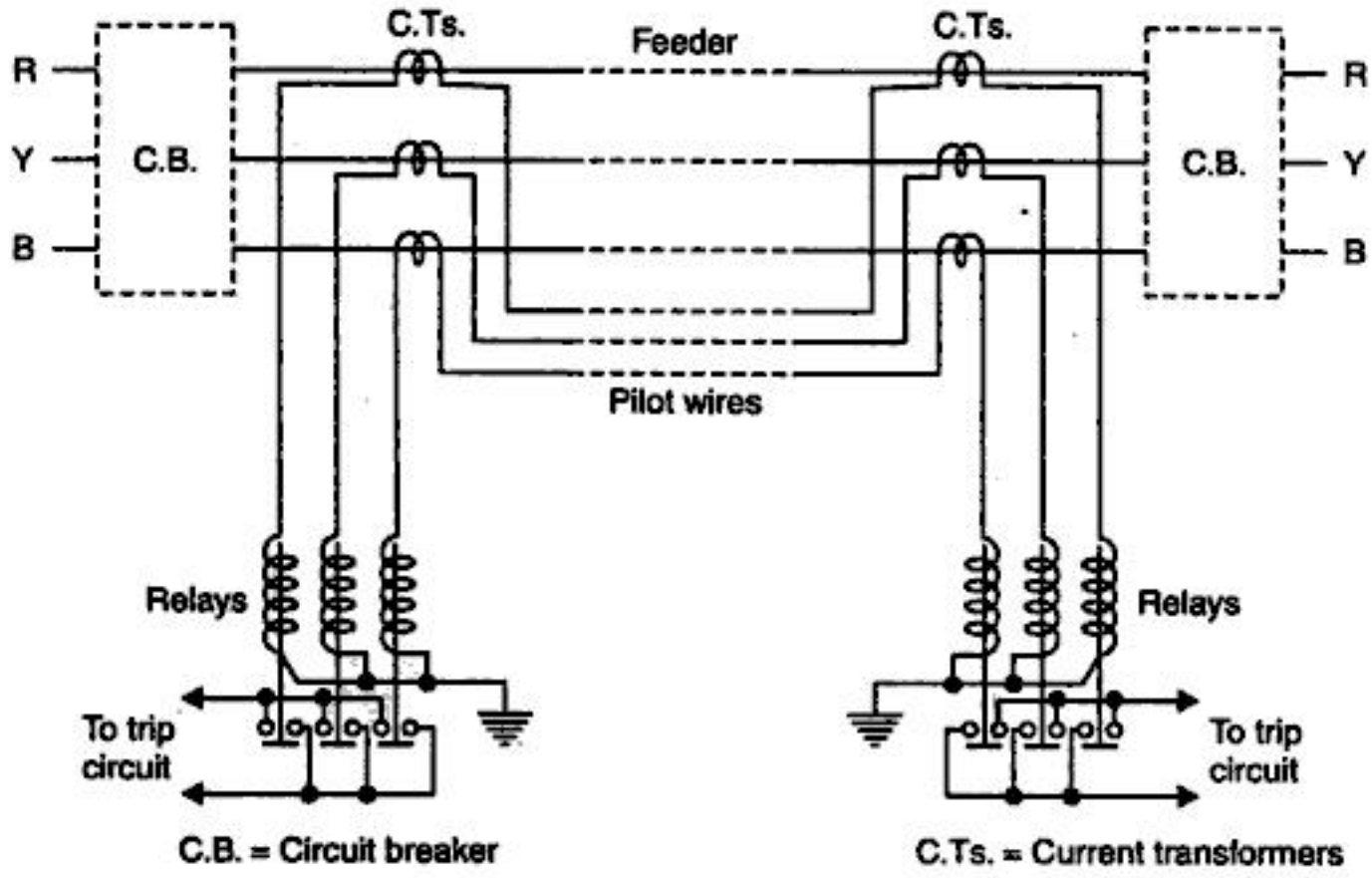

Fig. 25.7. Merz-Price protection system.

Advantages :

(*i*) This system can be employed for protection of both ring mains as well as feeders.

(*ii*) This system is independent of operating voltage and fault power factor.

(*iii*) This system provides instantaneous protection for ground faults, due to which the possibility of these faults involving other phases is reduced.

(*iv*) This system provides instantaneous relaying which reduces the amount of damage to overhead conductors resulting from arcing faults.

Disadvantages :

(*i*) A break in the pilot-wire makes the system inoperative.

(*ii*) It is essential to have accurate matching of current transformers.

(*iii*) In long transmission lines, charging current due to pilot-wire capacitance effects may be sufficient to cause relay operation even under normal working conditions.

(*iv*) Owing the constructional difficulties in matching the C.Ts., this system cannot be used for line voltages beyond 33 kV.

2. Translay system. The name *"Translay"* relates to the fact that the relay embodies a transformer feature.

- This system is similar to voltage balance system except that here *balance or opposition is between the voltages induced in the secondary windings wound on the relay magnets and not between the secondary voltages of the line current transformers.*

This system can be used for protection of single or 3-phase feeders, transformer feeders, feeders with a tee-off and parallel feeders against both earth and phase faults.

Fig. 25.8 shows a simple form of Translay protection for a ***single-phase feeder.*** Under healthy conditions, current transformers $C.T_1$ and $C.T_2$ carry equal currents and the coils 1 and 1′, induce equal e.m.fs. in the windings 2 and 2′ respectively. These latter windings are in opposition via the pilot wires with the operating windings 3 and 3′, in series with them. Thus no forward torque is exerted on the disc. When a fault occurs, the current through one C.T. is greater than that through the other. A small current circulates through the operating windings and pilot-wires, and when it reaches the set value it causes the relay to close the tripping circuit and to isolate the feeder.

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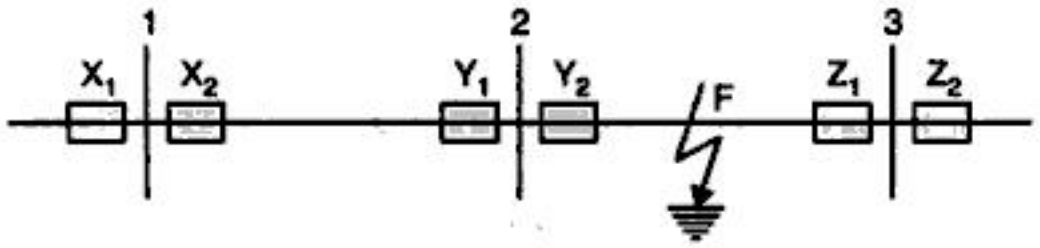

Fig. 25.15. Carrier blocking scheme.

The following are the "*advantages*" of carrier blocking scheme :

(*i*) The carrier signal is transferred over healthy line.

(*ii*) The carrier signal is sent only at fault condition.

3. *Carrier acceleration :*

The carrier acceleration is a scheme where the signal received from a relay at opposite end is utilised to extend the first step from 80% to 130% of the length of the protected line by shunting the timer element of the next zone as shown in Fig. 25.16.

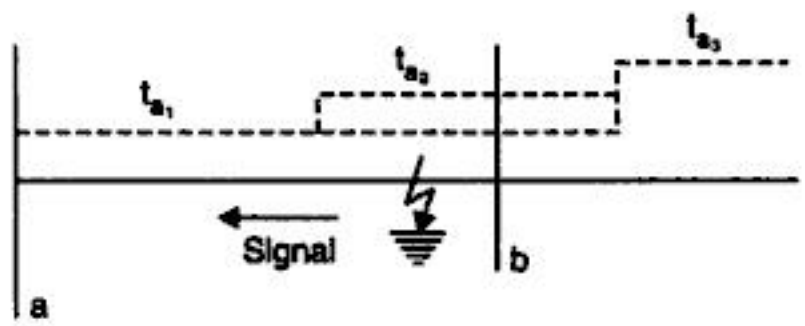

Fig. 25.16

HIGHLIGHTS

1. The various schemes of bus-bar protection are :
   (*i*) Differential protection. (*ii*) Fault bus protection.
   (*iii*) Bus protection by overcurrent relays. (*iv*) Static protection.
   (*v*) Overcurrent protection or distance protection as back up protection of bus-bar.
2. The most common methods of line/feeder protection are :
   (*i*) Time-graded overcurrent protection. (*ii*) Differential protection.
   (*iii*) Distance protection.

THEORETICAL QUESTIONS

1. State the importance of bus-bar protection.
2. State the reasons due to which bus fault occurs in a power system.
3. Name the various schemes of bus-bar protection.
4. Explain the following systems of bus-bar protection :
   (*i*) Differential protection (*ii*) Fault bus protection.
5. What are the requirements of protection of lines ?
6. Describe the time-graded overcurrent protection for
   (*i*) Radial feeders ; (*ii*) Parallel feeders ; (*iii*) Ring main system.
7. Describe the differential pilot-wire method of protection of feeders.

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26.4.1. Process of Lightning Discharge

The process / mechanism of lightning discharge is as follows :

When a charged cloud passes over the earth, it induces equal and opposite charges on the earth below. Fig. 26.2 shows a negatively charged cloud inducing a +ve charge on the earth below it. With the increase in charge of the cloud, the potential between cloud and earth increases and hence the gradient in the air also increases.

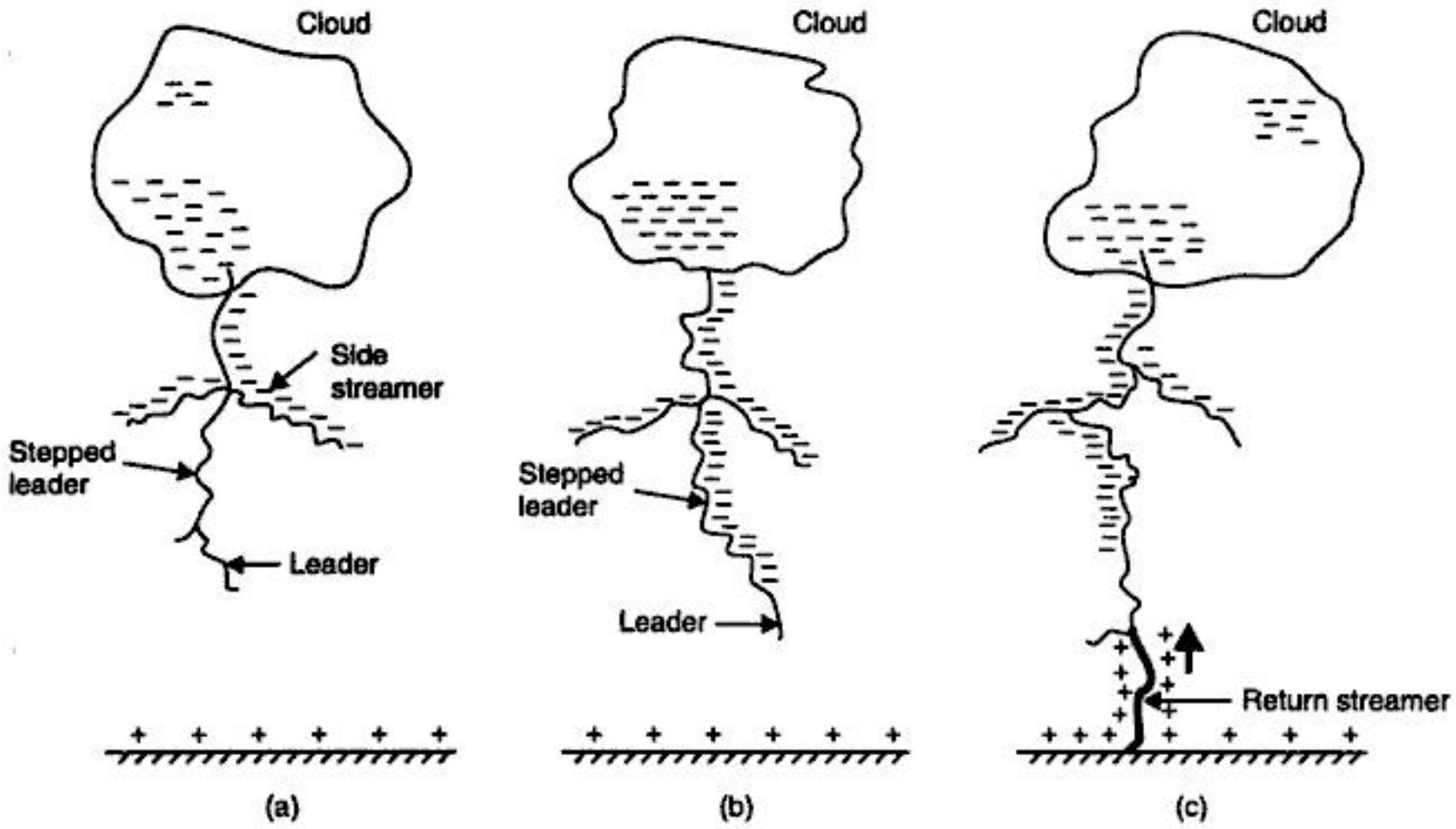

Fig. 26.2. Process of lightning discharge.

- *Refer to Fig. 26.2 (a).* Immediately after the air near the clouds breaks down, a streamer called a *leader / pilot streamer* starts from the cloud, and carrying charge with it moves towards the earth. The leader streamer with continue moving toward earth so long as the cloud, from which it originates feeds enough charge to it to maintain gradient at the tip of leader streamer above the strength of air. In case the gradient is not maintained, the leader streamer stops and the charge is dissipated without completion of the lightning stroke. As such the leader streamer will not reach the earth [Fig. 26.2 (*a*)].
- *Refer to Fig. 26.2 (b).* The leader streamer is continuing its journey towards earth until it makes contact with earth or some object on the earth. As the leader streamer moves towards earth, it is accompanied by luminescence which travel in jumps giving rise to stepped leaders (their velocity exceeds one-sixth of that of light and distance travelled is about 50 m in one step). The stepped leaders have adequate luminosity and give rise to first visual phenomenon of discharge.
- *Refer to Fig. 26.2 (c).* As soon as the leader streamer reaches near the earth, a *return streamer* shoots up from the earth to the cloud, following the same path as the main channel of the downward leader. This phenomenon causes a *sudden spark*, called *'lightning'*. Owing to neutralisation of much of the negative charge on the cloud, any further discharge from the cloud may have to originate from some other portion of it.

The following points about lightning discharge are worth noting :

(*i*) The currents during lightning discharge may be in the range of 10,000 to 90,000 A.

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3. Electrolyte arrester. An electrotype arrester operates on the fact that a thin film of aluminium hydroxide deposited on the aluminium plates immersed in electrolyte *acts as a high resistance to low voltage but a low resistance to voltage above a critical value.* Voltages more than 400 V (critical breakdown voltage) causes a puncture and flow of current to earth. When the voltage regains its normal value of 400 V, the arrester again offers high resistance in the path and leakage stops. The total critical value of voltage of such an arrester can be increased by arranging a number of films one above the other.

Since these arresters are very delicate, require daily supervision, and the film is required to be reformed whenever destroyed, therefore, these have become obsolete now-a-days.

4. Oxide film arrester. Its operating principle is based on the fact that *certain chemicals have the property to change rapidly from a good conductor to almost perfect insulator when slightly heated.*

It consists of 2.4 mm diameter pellets of *lead per oxide* with a thin porous coating of *litharge* arranged in a column and enclosed in a tube of diameter of about 6 cm and of height of 5 cm per kV of rating. Out of the two leads of the arrester upper is connected to the line, while the lower is connected to earth. The tube contains a series spark-gap. A single tube system is available for voltages upto 25 kV when the neutral is solidly earthed and 18 kV when neutral is isolated or earthed through an inductive coil. For use on higher voltages several units in series are employed

On the occurrence of overvoltage, an arc passes through the series spark gap and an additional voltage is applied to the pellet column and a discharge takes place. After the discharge, the resistance of the pellet column increases till only very small current can flow through it. This small current is finally interrupted by the series spark gap.

The *main advantage* of this type of arrester is that it does not require daily charging, and it may thus be installed at points on transmission systems where daily attendance is difficult or expensive to provide.

5. Thyrite arrester. *It is the most commonly used arrester for the protection against high dangerous voltages.*

It operates on the fact that *thyrite*, a dense inorganic compound of ceramic nature *has high resistance decreasing rapidly from high value to low value for currents of low value to those of high value. The current decreases 12.6 times on doubling the voltage.*

It consists of discs of 15 cm diameter and 19 mm thickness. Both the sides are metal sprayed so as to give electrical contact between consecutive discs. These discs are assembled inside the glazed porcelain container. It is used in conjunction with porcelain container.

On the occurrence of lightning stroke, a voltage is raised and breakdown of gap takes place, the resistance falls to a very low value and wave is discharged to earth. After the surge has passed the thyrite again comes back to its original position (there being no chemical change occurring simultaneously).

Advantages :

(*i*) The thyrite arrester discharges several thousands amperes without the slightest tendency to flash-over on the edges.

(*ii*) There is absolutely no time lag in its performance.

6. Expulsion type lightning arrester. This type of arrester is also called "***protector tube***" and is commonly used on system operating at voltages upto 33 kV. It is an improvement over the rod gap in that it *seals the flow of power frequency follow current.* Its application is normally limited to

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is the reactance due to the capacitance of the line to ground. The charging currents I_{CR}, I_{CY} and I_{CB} are balanced and their *result is zero, and no current flows to the earth.* Now consider a phase of earth fault in the line B say at point F. Under these circumstances, the faulty line takes up the earth potential while the potentials of the remaining two healthy phases R and Y rise from phase values to line values. The capacitance currents become unbalanced and fault current I_F flows through the faulty line, into the fault and return to the system via earth and through the earth capacitances C_R and C_Y. Thus fault current I_F has two components I_{BR} and I_{BY} which flow through capacitances C_R and C_Y respectively under the potential differences of V_{BR} and V_{BY} respectively. These currents lead their respective voltages by 90° and their vector sum is equal to fault current I_F as shown in Fig. 27.2 (*b*).

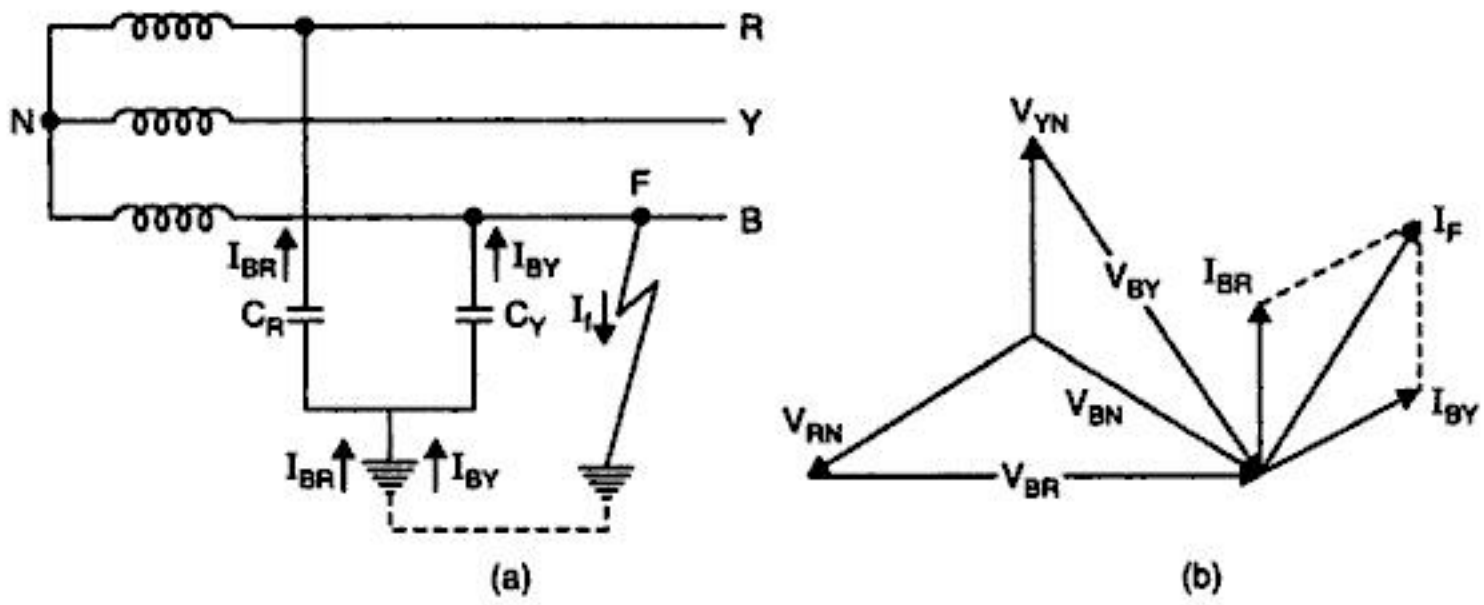

Fig. 27.2. A ground fault in one of the phases of the ungrounded system.

Since phase voltages are equal, say equal to V_{ph} and capacitances from line to ground are also equal, say equal to X_C, we have :

$$I_{BR} = \frac{V_{BR}}{X_C} = \frac{\sqrt{3}\, V_{ph}}{X_C}$$

Similarly, $$I_{RY} = \frac{V_{BY}}{X_C} = \frac{\sqrt{3}\, V_{ph}}{X_C},$$

and thus, $$I_F = \sqrt{3}\, I_{BR} = \sqrt{3} \times \frac{\sqrt{3}\, V_{ph}}{X_C} = \frac{3V_{ph}}{X_C} \qquad ...(27.1)$$

From the above discussion, the following *conclusions can be drawn :*

1. No zero sequence current.

2. Little interference with communication lines (since the fault current is small).

3. In case of one phase becoming earthed the voltages of the remaining two healthy phases to earth rise from their normal phase to neutral.

4. The capacitive current in the faulty phase is 3 times its normal value.

5. The capacitive current in the two healthy phases increased to $\sqrt{3}$ times their normal values.

6. The fault current in the overhead lines may be so small as to render automatic isolation by protective means difficult, if not impossible.

7. A capacitive fault current I_F flows into the earth. Such a current if exceeds 4 A, is sufficient to maintain an arc in the ionized path of the fault, even though the medium causing the fault has cleared itself. The persistency of the arc due to flow of capacitive current gives rise to a condition known as "*arcing ground*" in which cycle charging and discharging of the system capacity through

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In the case of star connected systems with earthed neutrals or delta connected systems with earthed artificial neutral point :

(*a*) the neutral point shall be earthed by not less than two separate and distinct connections with earth each having its own electrode at the generating station and at the sub-station and may be earthed at any other point, provided that no interference of any description is caused by such earthing ;

(*b*) in the event of an appreciable harmonic current flowing in the neutral connections so as to cause interference with communication circuits, the generator or transformer neutral shall be earthed through a suitable impedance.

2. Single-phase or extra-high voltage systems shall be earthed in a manner approved by the Inspector.

3. In the case of a system comprising electric supply lines having concentric cables, the external conductor shall be the one to be connected with earth.

4. Where a supplier purposes to connect with earth an existing system for use at high or extra-high voltage which has not either been so connected with earth, he shall give not less than fourteen days notice in writing together with particulars to the telegraph authority of the proposed connection with earth.

5. Where the earthing lead and earth connection are used only in connecting earthing guards created under high or extra high voltage overhead lines where they cross a telecommunication line or a railway line, and where such lines are equipped with earth leakage relays of a type and setting approved by the Inspector, the resistance shall not exceed 25 ohms.

6. In so far as the provisions of rule 61 are consistent with the provisions of this rule, all connections with earth shall also comply with the provisions of that rule.

HIGHLIGHTS

1. The process of connecting the neutral point of a supply system on the non-current carrying parts of electrical apparatus to the general mass of the earth in such a manner that at all times an immediate discharge of electric energy takes place without danger is called *earthing*.
2. *Methods of neutral earthing :*
   (*i*) Solid earthing
   (*ii*) Resistance earthing
   (*iii*) Reactance earthling
   (*iv*) Arc-suppression coil earthing (Resonant grounding)
   (*v*) Voltage transformer earthing.
3. When the access to the existing neutral is not possible or when the system is delta-connected and availability of neutral is essential *earthed transformers are used to create an artificial neutral.*

THEORETICAL QUESTIONS

1. Define the term "Earthing".
2. What are the functions of grounding in power system ?
3. State the advantages of neutral grounding of an electrical system.
4. What are the objects of earthing.
5. What is the necessity of neutral earthing ? Explain.

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OBJECTIVE TYPE QUESTIONS' BANK

Choose the Correct Answer :

1. A hydroelectric power station is commonly found in
   (*a*) desert areas (*b*) hilly areas
   (*c*) swamps (*d*) grasslands.
2. Bio-gas plants are suitable for
   (*a*) metallurgical industries (*b*) commercial complexes
   (*c*) rural areas (*d*) coal mines.
3. Condensers in thermal power plants for condensing
   (*a*) steam to water (*b*) water to ice
   (*c*) hydrogen gas to liquid hydrogen (*d*) carbon dioxide to dry ice.
4. Capacitance of a transmission line
   (*a*) increases (*b*) decreases
   (*c*) remains same (*d*) with increases in its length.
5. The angle of *A*, constant of the transmission line normally lies between
   (*a*) 90°—70° (*b*) 70°—40°
   (*c*) 40°—10° (*d*) 10°—0°.
6. For a long distance e.h.v. transmission line the receiving-end voltage under unloaded condition is
   (*a*) much lower than (*b*) lower than
   (*c*) equal to than (*d*) higher than.
   the sending-end voltage.
7. By increasing the transmission voltage to double of its original value the same power can be despatched keeping the line loss
   (*a*) equal to original value (*b*) half the original value
   (*c*) double the original value (*d*) one-fourth of original value.
8. ACSR conductors have
   (*a*) all conductors made of aluminium (*b*) outer conductors made of aluminium
   (*c*) inner conductors made of aluminium (*d*) no conductors made of aluminium.
9. Shunt capacitors in a sub-station
   (*a*) consume lagging var (*b*) deliver lagging var
   (*c*) consume active power (*d*) deliver active power.
10. Wavy structure of pin insulator increases its
    (*a*) mechanical strength (*b*) puncture strength
    (*c*) flashover strength (*d*) thermal strength.
11. Increase in frequency of transmission line causes
    (*a*) no change in line reactance (*b*) increase in line resistance
    (*c*) decrease in line resistance (*d*) decrease in line series reactance.

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58. Under frequency operation of power systems is undesirable as it causes
(*a*) damage to hydro units (*b*) damage to thermal units
(*c*) increased line charging requirements (*d*) reduces the line reactance.

59. Back-to-back HVDC is used to
(*a*) increase the transmission capability (*b*) decrease line losses
(*c*) provide stable interconnection (*d*) reduce voltage drop.

60. Most of the steam turbo alternators are wound for
(*a*) two poles (*b*) ten to twenty poles
(*c*) twenty to thirty poles (*d*) six poles.

61. If the frequency of a transmission system is changed from 50 Hz to 100 Hz, the string efficiency
(*a*) will increase (*b*) will decrease
(*c*) remains unchanged
(*d*) may increase or decrease depending on the line parameters.

62. The surge impedance of 50 miles long under-ground cable is 50 ohms. For a length of 25 miles, the impedance will be
(*a*) 26 ohms (*b*) 50 ohms
(*c*) 100 ohms (*d*) 12.5 ohms
(*e*) none of these.

63. In order to have lower cost of electrical energy generation it is required to have
(*a*) low load factor and diversity factor (*b*) low load factor but high diversity factor
(*c*) high load factor but low diversity factor (*d*) high load factor and high diversity factor.

64. Shunt compensation in a EHV line is resorted to
(*a*) improve the stability (*b*) reduce the fault level
(*c*) improve the voltage profile
(*d*) as a substitute to synchronous phase modifier.

65. The size of conductor on modern EHV lines is obtained based on
(*a*) voltage drop (*b*) current density
(*c*) corona (*d*) skin effect
(*e*) none of the above.

66. The presence of earth in case of overhead lines
(*a*) increases the capacitance (*b*) increases the inductance
(*c*) decreases the capacitance (*d*) decreases the inductance.

67. Phase modifier is normally installed in the case of
(*a*) short transmission lines (*b*) medium length lines
(*c*) long length lines (*d*) all length of lines.

68. Increase in temperature in overhead transmission lines causes
(*a*) increase in stress and length (*b*) decrease in stress and length
(*c*) decrease in stress but increase in length (*d*) none of the above.

69. High voltage long lines are transposed because then
(*a*) corona losses can be minimised (*b*) computation of inductance becomes easier
(*c*) voltage drops in the lines can be minimised
(*d*) phase voltage imbalances can be minimised.

70. If the separation between the three phases of a transmission system is increased then
(*a*) the inductance will increase and capacitance will remain unchanged
(*b*) both the inductance will increase and the capacitance will decrease

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195. The transfer of power between two stations is maximum when the phase displacement between the voltage of two stations is
(*a*) zero (*b*) 90°
(*c*) 120° (*d*) 180°.

196. A 100 MW alternator is connected to an infinite bus and its excitation is increased, then the terminal voltage of the alternator will
(*a*) rise (*b*) fall
(*c*) remain unaltered.

197. For bulk power transmission over long distance HVDC transmission is
(*a*) economically and technically superior to a.c. transmission
(*b*) not a good alternative to a.c. transmission
(*c*) not economically viable.

198. Series capacitors on transmission lines are of the little use when
(*a*) the load VAR requirement is small
(*b*) the load VAR requirement is large
(*c*) the load VAR requirement is fluctuating
(*d*) Series capacitors are never used on transmission lines.

199. Transmission of power by a.c. cables is impossible beyond
(*a*) 34-45 km (*b*) 500 km
(*c*) 300 km.

200. Inductance of a transmission line is of the order of
(*a*) 1 H/km (*b*) 1 mH/km
(*c*) 15 mH/km.

201. Standard domestic a.c. supply voltage in India is
(*a*) 220 volt (*b*) 230 volt
(*c*) 240 volt.

202. The total instantaneous power in a balanced three phase line
(*a*) varies at power frequency (*b*) varies at twice the power frequency
(*c*) is constant, independent of time.

203. A large diversity factor of the load in a power system
(*a*) reduces the installation cost (*b*) increases the installation cost
(*c*) does not affect the installation cost.

204. In a nuclear reactor thermal energy is obtained from
(*a*) fission of radioactive materials (*b*) fusion of radioactive materials
(*c*) burning of the fuel rods in oxygen.

205. Inductance of an overhead line, in comparison to that of a cable of same capacity is
(*a*) larger (*b*) smaller
(*c*) of the same order.

206. Proximity of a line to the earth surface
(*a*) does not affect its capacitance to neutral
(*b*) increases the capacitance to neutral
(*c*) decreases the capacitance to neutral.

207. For a given conductor the value of GMR is
(*a*) larger for capacitance calculation (*b*) large for inductance calculation
(*c*) same for both capacitance and inductance calculation.

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306. Efficiency is secondary consideration in case of
(*a*) peak load plants (*b*) base load plants
(*c*) both peak load and base load plants (*d*) none of the above.

307. For the same plant size, initial cost of which plant is the highest ?
(*a*) steam power plant (*b*) diesel power plant
(*c*) nuclear power plant (*d*) gas turbine plant.

308. The fact that a conductor carries more current on the surface as compared to core, is known as
(*a*) skin effect (*b*) corona
(*c*) permeability (*d*) unsymmetrical fault.

309. Presence of ozone as a result of corona is harmful because
(*a*) it gives bad odour (*b*) it corrodes the material
(*c*) it transfers energy to the ground (*d*) reduces power factor.

310. In a transmission line having negligible resistance, the surge impedance is
(*a*) $\sqrt{L+C}$ (*b*) $\sqrt{C/L}$
(*c*) $\sqrt{\frac{1}{CL}}$ (*d*) $\sqrt{L/C}$.

311. For 11 kV line, the capacitance per km per phase will be of the order of
(*a*) 1 Farad (*b*) 0.10 Farad
(*c*) 0.01 Farad (*d*) 0.01 μF.

312. Which distribution system is more reliable ?
(*a*) ring main system (*b*) tree system
(*c*) radial system (*d*) all are equally reliable.

313. The function of steel wire in an ACSR conductor is
(*a*) to take care of surges (*b*) to prevent corona
(*c*) to reduce inductance (*d*) to provide additional mechanical strength.

314. For a 66 kV line having span of 200 metres between towers, the approximate sag will be :
(*a*) 0.02 m (*b*) 0.2 m
(*c*) 2 m (*d*) 20 m.

315. In a sub-station the equipment used to limit short circuit current level is
(*a*) series reactor (*b*) coupling capacitor
(*c*) lightning switch (*d*) isolator.

316. A 30 km transmission line carrying power at 33 kV is known as
(*a*) short transmission line (*b*) long transmission line
(*c*) high power line (*d*) ultra high voltage line.

317. The permissible voltage variation in a distribution system is
(*a*) ± 0.1% (*b*) ± 1%
(*c*) ± 10% (*d*) ± 20%.

318. 750 kV is termed as
(*a*) medium high voltage (*b*) high voltage
(*c*) extra high voltage (*d*) ultra high voltage.

319. The sag of a transmission line is least affected by
(*a*) self weight of conductors (*b*) temperature of surrounding air
(*c*) current through conductor (*d*) ice deposited on conductor.

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About the Book

This book on **"Power System Engineering "** has been written for students preparing for B.E., B.Tech., A.M.I.E.(I) Section B, U.P.S.C.,and other Competitive Examinations. It comprises three parts: ***Part -I*** deals with **"Generation"**, ***Part- II*** with **"Transmission and Distribution"** while ***Part -III*** includes **"Switchgear and Protection"**.The book contains 28 chapters in all, at the end "Objective Type Question Bank" has also been added.

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- The presentation of the subject matter is very systematic and the language of the text is lucid, direct and easy to understand.
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- At the end of each chapter *Highlights, Objective Type Questions, Theoretical Questions and Unsolved Examples* have been added to make the book a complete and comprehensive unit in all respects.

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Er. R.K. Rajput, born on 15th September, 1944 (coincident with Engineer's Day) is a multi-disciplinary engineer. He obtained his *Master degree* in ***Mechanical Engineering*** (with Hons.-Gold Medal) from Thapar Institute of Engineering and Technology, Patiala. He is also a *Graduate Engineer* in ***Electrical Engineering.*** Apart from this he holds memberships of various professional bodies like Member Institution of Engineers (MIE); Member Indian Society of Technical Education (MISTE) and Member Solar Energy Society of India (MSESI). He is also a Chartered Engineer (India). He has served for several years as Principal of "Punjab College of Information Technology", Patiala and "Thapar Polytechnic, Patiala".

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He has earned, by dint of hard work and devotion to duty, the following awards/honours:
****Best Teacher (Academic) Award * Jawahar Lal Nehru Memorial Gold Medal for an outstanding research paper (Institution of Engineers) * Distinguished Author Award * Man of Achievement Award.***

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